REORGANIZATION BY ADAPTIVE AUTOMATION

by

MURRAY LEWIS BABCOCK

15 January 1960

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Technical Report No. 1
Contract Nonr 1834(21)
ONR Project No. NR 049-123

Sponsored by:
INFORMATION SYSTEMS BRANCH
MATHEMATICAL SCIENCES DIVISION
OFFICE OF NAVAL RESEARCH

ELECTRICAL ENGINEERING RESEARCH LABORATORY
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

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ABSTRACT

Using the present limited knowledge of nervous tissue of living organisms as a guide, an attempt is made to construct an adaptive automaton whose internal structure has a similarity to living nervous tissue.

Accepting the general contention that living organisms have qualities which show adaptation and self-organization as illustrated by evolution and the individual organism's ability to self-reproduce, the existence of these organisms is taken as a proof that adaptive systems are possible. Thus the philosophy and operation of a general "biological computer" is described, the internal components of this "computer" having functional operation very similar to that of a biological neuron--a basic component in nervous tissue.

After describing this general automaton, complete functional specifications of the individual elementary components are ideally established. Using these specifications of so-called "artificial neurons", an attempt to reduce the automaton to practice by the use of electronic techniques is made. In this reduction the elementary components are considered as highly versatile information processors, the result being an electronic model of an information system having some of the structural and functional characteristics of nervous tissue.

Several of these electronic elementary components have been constructed. Experimental tests on these components essentially corroborate the similarity desired between them and the biological neurons.

Initial tests on simple circuits containing these components indicate that interesting adaptive behavior is indeed possible with very small numbers of these components. For example, simple adaptive pattern recognizers, order

detectors, counters, etc. have been constructed. Even some autonomous pattern behavior has been detected. These basic processes of adaptation are presently of only the most elementary type, but with greater environmental complexity, which involves more elaborate input transducers, it is felt that much greater adaptive functional behavior is possible.

Certain unpredicted effects have arisen. For example, normally inactive portions of the automaton which are connected to the active portions only through the energy supply occasionally become active pulse-wise in synchronism with the autonomous components. This effect has a correspondence in the biological system where the alpha rhythm is present in the inactive cortex.

In short, a form of "biological computer" is now available which is extremely flexible in its operation and potential connectivities. When used as a standard analogue device it is useful for detail examination of the system functioning. When used in a manner similar to how a biologist examines a living operational system, the automaton may be used as a predictive device. This latter method is the manner in which the automaton was intended to be used and it is hoped that by this method knowledge of various systems will be gained and eventually used to construct more elaborate systems.

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1. INTRODUCTION

The following pages describe an attempt to construct an adaptive automaton whose internal structural features are believed to be modeled according to our present limited knowledge of biological nervous tissue.

It is generally accepted that the most conspicuous qualities of living organisms are their capabilities of adaptation and self-organization. For example, evolution and self-reproduction are usually cited as illustrative of these qualities. According to the pioneering work done in the first half of this century by Claude Bernard, Norbert Wiener, Warren McCulloch, and others, there seems to be no doubt today that these qualities can be achieved only by the use of a feedback loop consisting of the information flowing from the environment through the system and then back into the environment, where the system can then take cognizance of its state in the environment due to its own activity. We know at present that living organisms possess two major systems for internally processing this information, these being the endocrine system and the nervous system.

The work presented here will concentrate on some functional aspects of the nervous system only, since its structure seems more amenable to synthesizing its components by electrical circuits.

Since the basic component of nervous tissue is a separable entity, the neuron, the problem at present is that of the construction of a suitable model of a biological neuron and associated system. Since the nerve cells of the cortex are essentially all alike or very similar to each other, at least in appearance, the individual functional properties of neurons or of groups of neurons are not identifiable by their appearance or by their interconnectivity to each other. Therefore the model cannot be simply an analogue device in the usual connotation. It must be flexible enough in its operation to be used in its entirety or in sections, as part of a system or as the total system, as a control section or as a transmission section, as an input section or an output section; that is, it should have as many of the attributes of the biological nervous system as it is feasible to anticipate, plus attributes which will allow it to be used as a predictive model of general neuron activity. Therefore the model will be a "biological computer" not only in the general meaning of an analogue of a natural biological system but also in the much broader sense.

The purpose then of this thesis is to describe in rather general terms the philosophy and operation of such a model and to describe in detail, specifications of the various components. The circuitry of a special electrical automaton which is a special case of the general model will be illustrated and finally, some simple experimental results obtained with this very limited automaton will be presented.

2. NEUROLOGICAL SUMMARY

To solve the problem posed in Chapter 1--that is, the construction of an adaptive system which shows some of the behavior characteristics of a biological system--it is certainly necessary to obtain as much information about that biological system as is deemed pertinent. This chapter will discuss the parts of the nervous system and the data about it which will be used in later sections to develop the final solution which, it is hoped, does indeed have similar characteristics. Since the present system is to be constructed with electronic and associated parts, the emphasis in the following discussion will be on the electrical effects and in general the electrophysiology of the nervous system. That is, even though the functioning of the various components of any nervous system is primarily chemical in nature, only that part of the chemistry which seems necessary to explain superficially the electrical effects which result will be discussed.

The basic doctrine of nervous functioning asserts that the nerve cell and its associated appendages--together called the neuron--is the basic unit of the nervous system and is directly involved in all nervous functioning and that all nerve fibers which transmit information are merely anatomical extensions of the neuron[6]. Therefore, the neuron is most fundamental in a discussion of any biological nervous system.

Figure 1[*] is a drawing of a pyramidal neuron from the sensori-motor cortex of a cat. This drawing was made from a tracing of three micro-photographs and shows very clearly the essential parts of the neuron, these parts being typical of the two basic groups of neurons, pyramidal and stellate, found in the cortex

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[*] Reprinted with permission from D.A. Sholl, "The Organization of the Cerebral Cortex," 1956, John Wiley and Sons, Inc., p. 3.

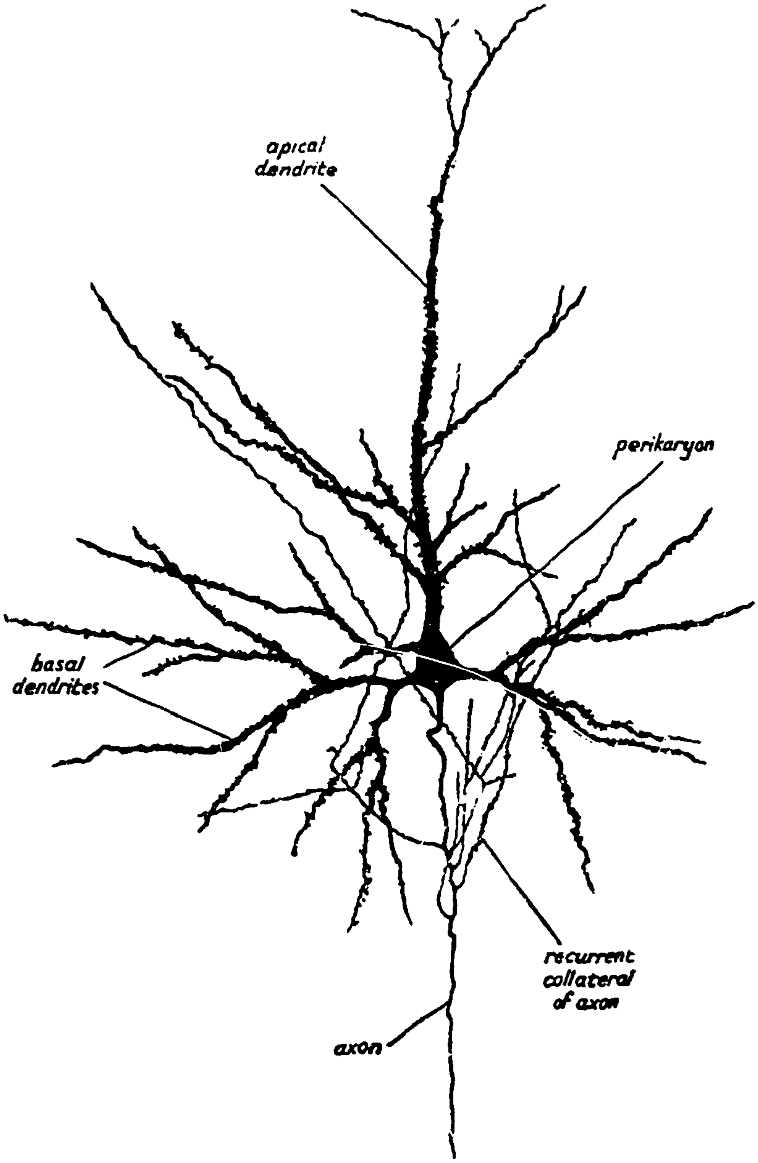

Figure 1 Pyramidal Neuron from the Sensori-Motor Cortex of a Cat

of most mammals[34]. As to size of a neuron, a typical neuron may have a perikaryon which measures from 10 to 100 microns across[10]. There are about 10^{10} such neurons in the human cortex, their density varying throughout the cortex according to the various functional regions. For example, in the human cortex, the motor area has the lowest density and the visual area has the highest density, their average densities being in the ratio of about 1:3. With respect to over-all average densities of neurons the following table taken from Sholl is enlightening[34].

TABLE I

Cerebral Cortex Neuron Density in Various Animal Species

Species	Cerebral Cortex Neuron Density in neurons per .001 cubic millimeter
Mouse	142.5
Rat	105.0
Guinea pig	52.5
Rabbit	43.8
Cat	30.8
Dog	24.5
Monkey	21.5
Man	10.5
Whale	6.8
Elephant	6.9

Using a value of 10 neurons per .001 cubic millimeter for the cortex neuron density in man and a value of 10 microns for the diameter of a typical perikaryon, the result is that perhaps one to five percent of the total volume of the cortex is occupied by the perikaryon, leaving the rest to be filled with ramifications of the dendrites, axons, and general cell nourishment supply.

The system of communication between various points in the cortex is actually, at first thought, very simple, the information being passed from neuron to neuron in a sort of chain linkage sequence, information arriving at the dendrites of any neuron being processed in a very particular manner and then being transmitted by the perikaryon down the axon to arrive at a dendrite or dendrites of the next neurons in the information transmission chain. However, when it is realized that as many as perhaps 5000 neurons may be influenced by only one neuron preceding them in a chain, and that each of these 5000 neurons may in turn influence that many more, then some idea of the complexity of the communication system may be obtained. When the various manners in which each neuron can be influenced--to be discussed later--are considered, then the complexity becomes very large indeed.

Figure 2* is a photograph of a section from the sensori-motor cortex of a cat. The method of staining the section--the Golgi-Cox method--is such that only about 1½ percent of the total number of perikarya and dendrites are made visible and so the total number of neurons in this section is about 65 times greater than that shown, thus illustrating the almost impossible complexity present. Note the 250 micron dimension key in the lower right corner of the photograph.

It is not the intent of the present thesis, however, to attempt to approach this complex a problem, but it is more the intent to separate the problem into an infinitely smaller problem and to study only a very small sub-section, namely that of the informational operation of the basic neurons with perhaps some interaction principles. Therefore the neuron will now be

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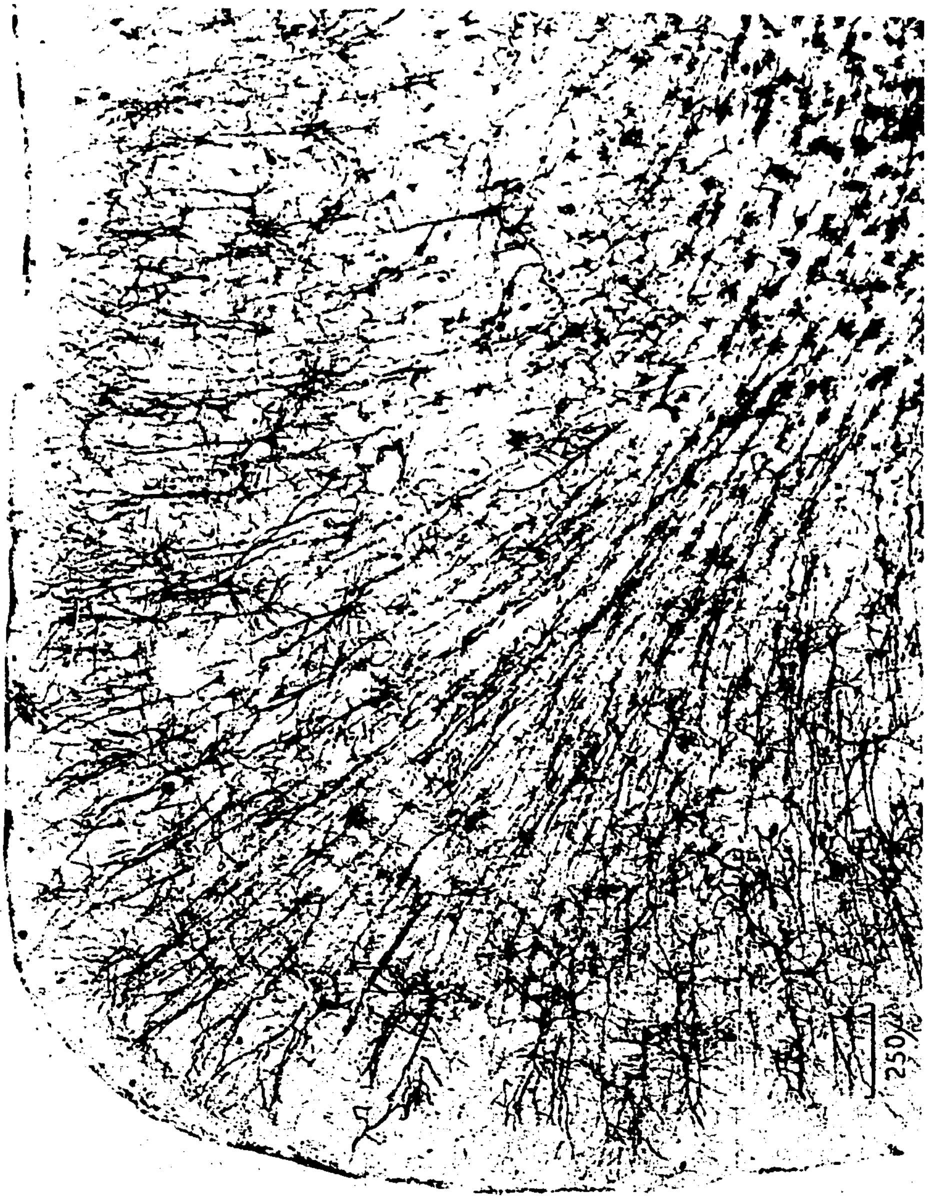

Figure 2. Section from the Sensori-Motor Cortex of a Cat

described with reference to its role as an information processor. Reference to Figure 1 in the following discussion will be helpful.

Assume that there exists some neurons in a neuron net and that information is being transmitted through this net. The information is in the form of pulse interval modulated signals. That is, the information which leaves a neuron and enters the next postceeding neuron is in the form of electrical pulses of standard amplitude and length with the intervals between pulses being variable. These pulses originate in the perikaryon of the neuron. From here they propagate down the axon of the neuron in a manner to be described later. The axon is located such or is ramified so that it comes in close contact with the ramifications of dendrites of other postceeding neurons. These contacts may also be on the main cell body as well as on the dendrites. The contacts, known as synaptic knobs and/or boutons, have a vary particular function to be described later, but at present they can be considered as labile connections between an axon and a dendrite or perikaryon. Under the influence of the pulses from many different axons--just how many pulses and the time relationships between the pulses being dependent upon the physical location of the bouton, its labile state, and the threshold of the particular neuron under consideration--the perikaryon will produce a pulse output, that is, it will fire. Thus a complete transition of a pulse from one neuron through the next postceeding neuron in the information chain has been qualitatively described. To better understand some of the details and to place quantitative values on some of the variables, the chemical model of a nerve fiber will now be described.

A nerve fiber may be regarded as an indefinitely long cylinder of reasonably uniform diameter which is filled with a watery medium of special composition, known as axoplasm. The fiber is immersed in a watery medium of a completely different composition, some filtrate of blood. The cylinder itself is an exceedingly thin plasma membrane of lipoid-protein structure which is only directly observable by means of an electron-microscope, its thickness being only from 50 to 100 Angstroms. Involved in the ionic hypothesis of the operation of the nerve fiber are essentially only three elementary ions: sodium, potassium, and chloride. The membrane in its resting state--i.e., when no electrical impulses are being transmitted by the fiber--is readily permeable to potassium and chloride ions which diffuse through it and due to different concentrations of the different ions involved both inside and outside the cylinder establish a Donnan potential whose magnitude is about 75 to 100 millivolts.[10] The inside of the cylinder is negative with respect to the outside. The resting membrane is only sparingly permeable to the sodium ions with the result that a small number of them diffuse into the interior of the cylinder continuously. To prevent this diffusion of sodium ions from disrupting the equilibrium established by the potassium and chloride ions, a sodium ion pump mechanism is hypothesized. This sodium-pump is located in the membrane and is driven in some manner from metabolic reactions within the fiber. By continuously removing the sodium ions from the interior of the fiber the sodium-pump keeps the concentration of sodium inside the nerve fiber at about 10 percent of the external concentration.

A nerve impulse is initiated and transmitted in the following manner. The resting potential of the membrane is slightly diminished by an applied electric current or by a flow of electric current in an adjacent section of the membrane. This causes the membrane to develop a high specific permeability to sodium ions by means of some "sodium-carrier" mechanism.[10] Thus the sodium ions rush inwards through the membrane and, being positively charged, rapidly begin to neutralize the existing resting negative charge. The sodium ion current inwards through the membrane is self-catalytic; that is, as the current increases, the permeability of the membrane to sodium increases, resulting in a self-regenerating feedback. This process continues until the original charge inside the fiber has not only been neutralized but has actually become somewhat positive with respect to the outside charge. At the same time that the "sodium-carrier" mechanism is beginning to fail when the nerve impulse is at its peak value, the potassium permeability of the membrane is greatly increased above its normal resting value and the potassium ions flow out of the interior of the nerve. In this way, the potential difference across the membrane is rapidly returned to its resting value.

With the above explanation, it is immediately apparent how an impulse of potential is transmitted along a nerve fiber, for any change in potential difference across a region of membrane will cause a current to flow in an adjacent region. This current will depolarize the adjacent region and thus inaugurate the chemical action explained previously. Thus a "smoke ring" of current will progress down the fiber, appearing electrically as a negative voltage pulse whose amplitude is approximately equal to the resting potential of the membrane, i.e., about 100 millivolts and whose width is about 1 millisecond.

Figure 3* is a drawing of a typical pulse obtained from a squid giant axon.[10] The pulse was detected by means of an internal electrode inserted longitudinally into the nerve fiber which had been removed from the squid and placed in an appropriate chemical solution. The nerve was then artificially excited. The pulse is drawn so that it shows the potential of the outside electrode with respect to the inside electrode.

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*Reprinted with permission from J. C. Eccles, "The Neurophysiological Basis of Mind," 1953, Clarenden Press, p. 31.

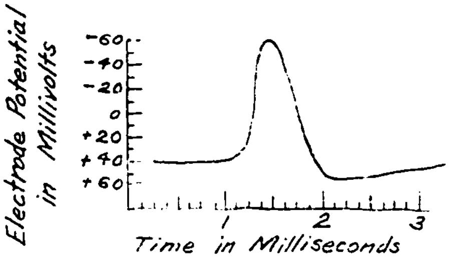

Figure 3. Action Potential Established by a Single Propagated Impulse as Recorded in a Squid Giant Axon.

The preceding hypothesis of ionic operation of the nerve fiber when its equilibrium is disturbed implies that the resulting electrical pulse output is secondary to the relationship of the membrane and its associated ionic media on either side of it. However, since the present interest is primarily of an electrical nature, these pulses may be considered primary, and the nerve fiber considered only electrophysiologically.

One of the electrical characteristics of a nerve fiber which may be of interest since there is movement of charge through the membrane is the conductance of the membrane. This has been measured for several nerve fiber membranes and the resulting conductivities range from 140×10^{-5} mho per square centimeter for a squid giant nerve fiber to 8×10^{-5} mho per square centimeter for a sepia giant fiber. This latter is extremely small when compared to that of an equal thickness of sea-water similar to that in which the sepia axon is immersed, the sea-water having a conductivity of 4.5×10^{4} mho per square centimeter--i.e. a value 5.5×10^{8} times greater than that of the sepia fiber membrane.[10]

Because the electrical conductance of the membrane is extremely low, the membrane with its positive charges on the outside and its negative charges on the inside may be thought to have the properties of a capacitor. The sizes of the membrane capacities of the squid and sepia nerve fibers range from 1.0 to 1.3 microfarad per square centimeter. If the potential across the membrane is 100 millivolts and the thickness of the membrane is 50 Angstroms, then the electric field strength in the membrane can become as great as 2×10^5 volts per centimeter. This value is about 6 or 7 times greater than the electric field strength required to break down an equal thickness layer of dry air at sea level pressure.

Since the membrane has an electrical conductance and capacitance, any change in potential across the membrane will decay exponentially with time, as in any resistance-capacitance network, with a decay constant equal to the product of the resistance per unit area and the capacitance per unit area of the membrane. This time constant has been measured with the following typical results: 1 millisecond for the squid fiber, 13 milliseconds for the sepia fiber, and 4 milliseconds for the cat motoneurons.[10]

One other electrical characteristic may be of interest. That is the specific resistance of the axoplasm inside the nerve cylinder. This has been indirectly evaluated to be 30 to 60 ohm centimeter for giant axons of marine invertebrates and about 110 ohm centimeter for some frog nerve fibers.[10]

The nerve fibers mentioned in all the previous explanations are nothing more than the axons of neurons. There is very little difference electrically between the perikaryon and the axon and so the method of initiating and transmitting a pulse in the parikaryon is essentially the same as that given for the axon. The next question then seems to be how the impulse in the perikaryon of a given neuron is triggered by pulses arriving from other neurons. That is, what is the function of the dendrites and the boutons in depolarizing a localized region of the perikaryon or even the axon to the critical value so that the potential decrease becomes self-regenerating and an output pulse from the neuron results?

Assume that many pulses are active on various dendrites of a neuron, these pulses having gotten through the synaptic junction region. This is the region between the dendrite and the preceding axon and will be discussed later. The pulses on the dendrites travel decrementally along the dendrite since in the instance of the dendrite, it is such that self-regeneration of the pulse is restricted to only the subsynaptic membrane--i.e. the membrane of the dendrite immediately adjacent to the bouton.[10] Thus the pulse travels along the dendrite as if the dendrite were a transmission line with a given propagation constant. As a result, many pulses arrive at the perikaryon from many different dendrites and from many different synaptic regions. At the perikaryon, the potential across any region of the perikaryon membrane is the sum of all the pulse potentials active at that region. Remembering that the pulses have traveled various distances along the dendrites and that even originally at the various synaptic junctions, the pulses varied in amplitude and time, it is apparent that the potential of the perikaryon membrane is a combination spacial and temporal summation of the pulses influencing the entire dendritic region of the neuron. When this summation potential exceeds the critical potential at which the "sodium-carrier" mechanism becomes self-regenerative--this critical potential will henceforth be called the threshold potential--at any region of the perikaryon or even on certain regions of the axon, then a pulse is generated at that point and is transmitted throughout the axonal region of the neuron. The threshold is about 10% of the resting membrane potential and is a depolarizing potential.

The synaptic knobs, known also as boutons, are extremely important functionally in the operation of the neurons. It is believed that these are the main labile units in the biological nervous system, although certainly not the only ones. Within the synaptic junction region, which is the region of connectivity between the axon of one neuron and the dendrites, perikaryon, and in some instances also the axon of the immediately post-ceeding influenced neuron, is contained the long-time storage units of the neurons and consequently of the nervous system. These plastic storage units store information of the type related to the past use and history of the junction. That is, the boutons vary in such a manner, at present not well understood, that the pulse effect from axon to dendrite is facilitated as the total information transferred across the junction is increased. Therefore, certain pulse conduction paths from axon to dendrite have greater influence on the output pulse of the perikaryon than do other paths. In this way, it is apparent that memory patterns of events can be stored as conduction paths within a neuron net.

There is apparently no actual connection between the axon and the dendrite at the synapse but it is believed that a "chemical transmitter" mechanism[10] is active in transferring the effect of a pulse in an axon to a nearby dendrite at the synapse. However, this point need not be dwelt upon since only the total effect is important.

A few quantitative details about the size and number of synaptic knobs per neuron may be of interest. Synaptic knobs having a diameter ranging from 0.5 micron to 2 microns have been found in the spinal cord. Any neuron surface is fairly well covered with these knobs, as much as 40 percent of the surface of the perikaryon and dendrites of a motoneurone, for example, with a total of over 400 knobs having been counted on one motoneurone.[10] Figure 4* is a photograph of a model of the perikaryon and large dendritic stumps of a mammalian motoneurone showing the synaptic knobs attached to the surface.

The storage of information in the synaptic region can be summarized quantitatively as follows:[10] The facilitation which occurs after each active pulse at the synaptic knob decays with a time constant of about 4 milliseconds, the normal decay of a regenerative pulse. The facilitation which results after many thousands of conditioning pulses at the synaptic knob decays with a time constant of about 80 seconds--i.e. at a rate about 2×10^4 times less than the single pulse facilitation. After the conditioned facilitation there is a period of residual facilitation which decays with a time constant of about 16×10^3 seconds--about 4.5 hours. This is a rate of decrease of about 4×10^6 times less than the single pulse facilitation.

Eccles[10] summarizes the excitatory action of a neuron in the following manner:

> "In synaptic excitatory action the following sequence of events occur when a presynaptic impulse propagates into a synaptic knob.
>
> 1. A brief delay of 0.3 to 0.4 millisecond.
>
> 2. The development of an intense brief depolarization of the subsynaptic membrane with a total duration of about 0.5 millisecond. This effect is attributable to a net inward movement of cations, though possibly a net outward anion movement might contribute.
>
> 3. Due to local current flow into this "sink" there is depolarization of the surface membrane of the soma (perykaryon) dendrites, and adjacent segments of the axon. This current also

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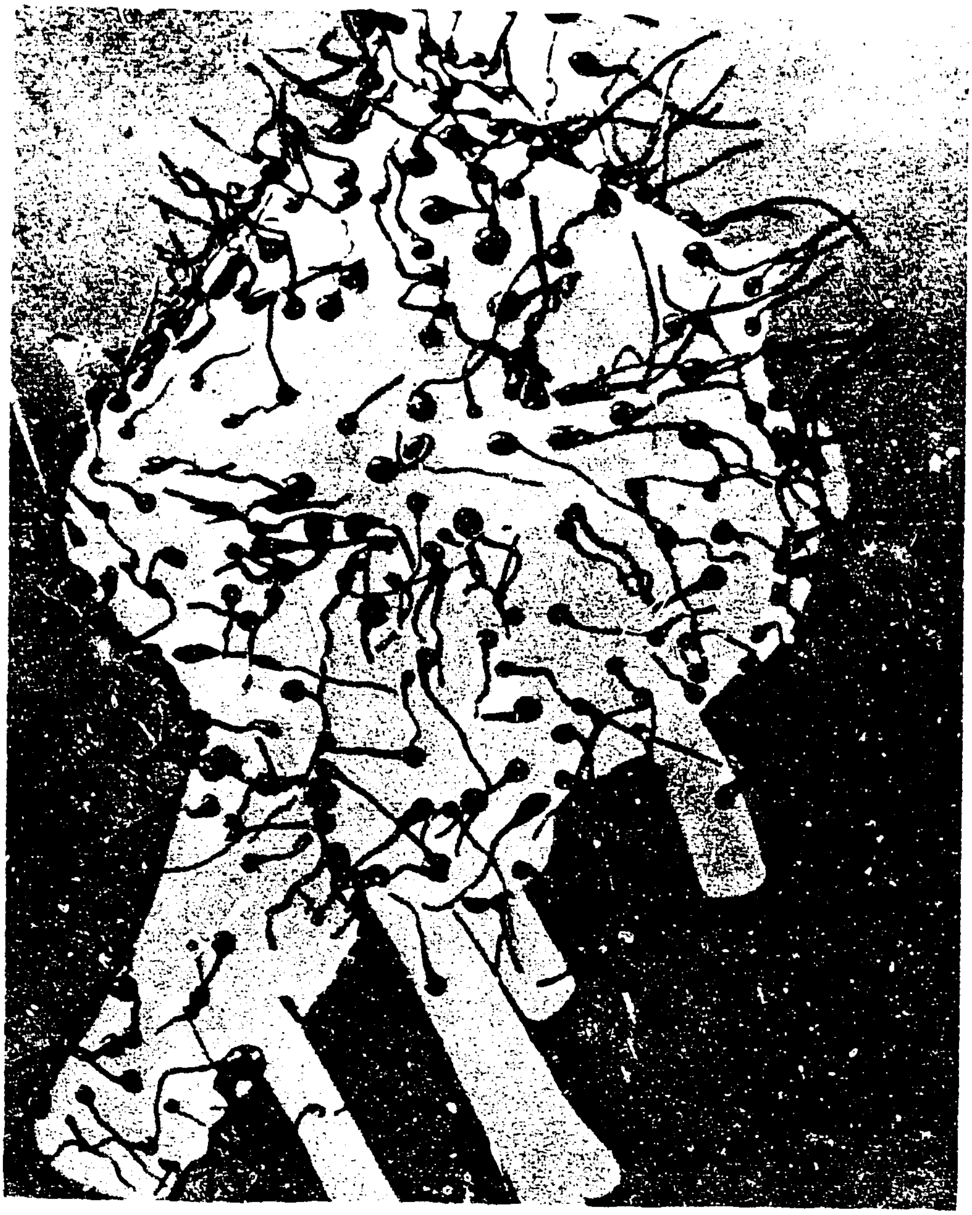

Figure 4. Model of the Perikaryon and Large Dendritic Stumps of a Mammalian Motoneurone

> generates the so-called focal and ventral-root synaptic potentials. Effects 2 and 3 together give the post-synaptic potential as recorded intracellularly.
>
> 4. If the depolarization of some part of the membrane reaches a critical degree, an impulse is generated and spreads over the soma and dendrites and down the axon, i.e. there is a reflex discharge.
>
> 5. Such an impulse destroys all the preformed post-synaptic potentials and is followed by the large positive after-potential that is characteristic of the neurone.
>
> 6. If no impulse is generated, the post-synaptic potential decays exponentially with the electric time-constant of the neuronal surface membrane, which is about 4 milliseconds. However, it appears that the peak of the post-synaptic potential is usually slightly prolonged by the depolarizing action of local responses of the post-synaptic membrane.
>
> Each presynaptic impulse independently produces its own post-synaptic potential. Generation of an impulse is dependent on the summation of such unitary post-synaptic potentials to give the critical level of depolarization."

Only excitatory action by impulses have been spoken of thus far. These have caused a depolarization of the nerve fiber membrane with the ultimate production of an output pulse provided the depolarization was great enough. One might ask, however, if instead of depolarizing the membrane, what would happen if it were hyperpolarized and if such an operation of the membrane does take place? The answer to the first part is that the membrane would be inhibited from "sodium-carrier" mechanism depolarization and the answer to the second part is that membranes do undergo this hyperpolarization by a process called inhibition.

The hyperpolarization caused by inhibition has been detected and measured by intracellular electrodes, the interior of the membrane becoming more negative in potential and the exterior of the membrane becoming more positive. There is as yet however, no general agreement as to how this hyperpolarization occurs nor as to how some pulses active at certain synaptic knobs cause depolarization and other pulses active at other synaptic knobs cause hyperpolarization.[10] Eccles concludes that inhibitory synaptic action is caused by some specific "chemical transmitter" substance being liberated from the inhibitory synaptic knobs just as excitatory synaptic action is caused by some "chemical transmitter" substance being liberated from the excitatory synaptic knobs.[10]

The electrical effects of inhibition are practically the inverse of excitation. That is to say, pulses which cause a region of nerve membrane to be depolarized have their exact counterparts in pulses which cause a region to be hyperpolarized by the same amount. Under ideal conditions of certain size pulses and location of the given region of membrane, an excitatory pulse and an inhibitory pulse would exactly cancel each other in their effects on the potential difference across the membrane. Therefore the inhibition may be considered as a pulse by pulse inhibition just as the excitation may be considered as a pulse by pulse excitation.

One other major point about a neuron remains to be discussed before leaving this section. That is the threshold of a neuron and how it enters into the over-all operation of the neuron and its net and how the threshold changes with activity and time. This threshold is considered to be rather important in the neuronal net operation since its value directly affects the production of an output impulse by a neuron.

The threshold--i.e. the critical value of potential change across a nerve fiber to cause an impulse--is about 10 percent of the total membrane potential difference. Therefore, any change in the potential across the membrane will affect the threshold. Since the potential is a function of the various concentrations of potassium, chloride, and sodium ions on both sides of the membrane, anything which changes these concentrations will change the potential. Thus the chemical environment of the neuron can change its threshold or the chemical nourishment which changes the ion concentration inside a neuron can change its threshold. For example, hormones, enzymes, drugs such as tranquilizers and stimulants, and so forth, can change the chemical ion concentration about the nerve fiber membrane. These changes in threshold are rather slow as compared to the previously mentioned normal inputs to the neuron but they are nevertheless very important, since these changes will certainly determine the over-all activity of the nervous system. The threshold changes caused by the above chemical concentration changes are the result of additions or depletions to the neurons through the blood supply and associated body cell nourishment sources. Therefore these changes are regional since many neurons in given neighborhoods are affected. These chemical inputs--if they may be called that--are then very slow changing inputs of a non-individual neuron variety as opposed to the previous pulse type inputs which are very rapid changes and which are of an individual neuron variety.

In addition to the chemical input threshold changes as just indicated, there is also a fatigue effect of the chemically determined threshold. For example, the interior of the nerve can be depleted chemically by continuously high output pulse repetition rates since some potassium ions flow out from the interior of the nerve fiber each time a pulse is developed or transmitted and if the pulse repetition rate exceeds the value at which the potassium ions can be replenished, then ultimately the output repetition rate must decrease.

Having now discussed various facts about the neuron, a short qualitative summary is in order before proceeding to a short discussion of the cortex region of the nervous system and the connectivities between neurons present in the cortex. The neuron can be briefly summarized as follows:

1. The neuron is a functional unit which utilizes as its output a pulsed code which is an all - or - none device. This pulsed form is only characteristic of the axon portion of the neuron.

2. The responses of most parts of the neuron as a result of input pulses do not determine output pulses directly, but help to determine the initiation of an impulse at some critical region of the perikaryon or base of the axon.

3. There is decremental conduction along or through the dendritic region of the neuron, but in the axon and axon region the conduction is decrement free--i.e. no attenuation.

4. The synaptic regions of the neuron are the malleable--i.e. labile--portions of the neuron where variable facilitations of the incoming pulses are experienced. These regions are the plastic storage units of the nervous system.

The neurons which have been discussed thus far have not been of any specific type, although some of the data have of necessity been rather specialized with respect to the source of the neuron--i.e. its original host such as squid, crab, frog, cat, human, etc. It is generally accepted that neurons are rather the same functionally, no matter where they are topologically located, although certain rather general classifications of neurons can be made such as efferent or sensory neurons, afferent or motoneurones, and so forth. These classifications are rather of a specific use classification, however, and not an internal functioning classification.

Therefore the neurons in the cerebral cortex probably function in the same manner as has been described for the rest of the neurons.

The cerebral cortex is a rather extensive convoluted layer of neurons, the average thickness of which is about one-quarter of a centimeter, the total surface area of both hemispheres is about 2300 square centimeters, the total volume is about 575 cubic centimeters, and the total weight is about 1350 grams.[34] The total number of neurons contained within this cortex is between 10^9 and 10^{10}. Each neuron may influence by its axon and adjacent dendrites from other neurons as many as 5000 other neurons. Thus it is apparent that amongst the problems related to the organization of the cortex are the total number of neurons involved, and the connectivities between neurons, since large groups of neurons are always active when any activity of the cortex is considered. These problems then are obviously of a statistical nature.

However, as indicated previously, it is not the problem of this thesis to study any such gross a problem, the only interest at present being to study the operation of small groups of artificial elementary components and their connectivities, these artificial elementary components having some of the electrical characteristics of a biological neuron. The philosophy involved in this problem and some of the past and present approaches to the realization of an automaton to answer some of the questions involved will be discussed in the next chapter.

3. PHILOSOPHY AND MODELS OF ADAPTIVE AUTOMATON

3.1 Philosophy

The problem that now must be answered seems to be one of method and magnitude also. For example, it has been stated that there are about 10^{10} neurons in the human cortex. A moments thought will surely reveal the huge task of attempting an analysis of such a system, even in very gross terms; for assuming only one percent of the neurons are necessary, the result is still 10^8 elements. If these elements are of the simplest type of binary output device, this means that there are 2^{10^8} (i.e. about $10^{3 \times 10}$) possible output states of the system. But this is an extremely simple approximation because the input conditions have not been stated. When even the simplest input conditions are assumed, such as each typical neuron having a minimum of 100 bifurcations in its dendritic structure, then each neuron has as many as 4^{10^2} possible input states. Therefore a conservative estimate of $(4^{10^2})^{10^8}$ -- i.e. about $10^{6 \times 10^9}$ -- possible states exists for the system. Therefore the model of the biological system will certainly be restricted to something considerably less in number of total elements.

Again, considering the number of elements which certainly are sufficient, the question arises as to just how many may be necessary. This question cannot, at present, be answered since it would involve at least some additional knowledge and understanding about the internal operation and connectivities involved in the cortex. To arrive at even a rough estimate of the total number of elements involves a guess, but it is known that certain animals of a very limited intelligence have only a few hundred neurons--for example, the earthworm has about 200. Therefore, it seems reasonable that the total number of elements required for a machine of limited biological operational behavior will be between 50 and 150, or possibly 200.

At present this seems to be about all one can say with respect to the magnitude of the system. It is now, perhaps, in order to discuss the method of arriving at the structural details and the philosophy of the individual elementary components--artificial neurons as they are sometimes known. However, before discussing what appears to be at least two approaches to this problem of method, some general thoughts about the system will be stated.

It was stated in the introduction that the basic interest is that of the design of biological computers. As such, certain limitations of design seem to have been automatically implied. For example, the system will be composed of elementary components whose functional operation is fairly complex compared to that of the general analog or digital computer. That is, the elementary components must each be capable of performing many operations which are delegated to different parts of the ordinary computers--for example, input, output, addition, control, storage, etc. This is to say that the system envisaged should not be made of many different types of elementary components, each with its particular function, but should be constructed of a minimal number of reasonably complex functional types of elements so that the operations involved in the system adapting to its environment will be distributed functionally throughout the totality of elements.

With regard to the adaptation of the system to its environment, a statement can be made about what is not wanted. This is: adaptation by total enumeration of all previous system fact history with later adaptation by means of enumeration and decision based upon that enumeration. This statement requires some explanation.

One manner by which any system, biological or artificial, could adapt to its environment would be to store all its experiences in a fact catalog type storage which was complete in all respects. As new experiences were met, the total fact storage would grow and continue to do so indefinitely throughout the system's existence. As the system met a particular condition in its environment it would search its catalog storage systematically and if the condition had been met previously, it would react according to its previous successful reaction. If the condition were a new one in its existence, it would have no basis for any particular reaction and so would react randomly, but would record that reaction. If the reaction proved successful from an existence criterion, the system would henceforth react to identical conditions in the same manner. If the reaction were in some manner unsuccessful but the system still survived, then the next identical condition of the system and environment would be met with a different reaction. And so the process would continue throughout the system's existence.

There are several undesirable features and weaknesses to the above method of behavior determination. The first, and most obvious, is the large storage required if the system is to completely catalog all details of its experience for a considerable time of existence. The second undesirable feature follows directly from the first and is the time required for the system to make a decision each time it encountered a condition of the environment. This would become greater and greater as the experience of the system increased, and could become excessive. The third feature could be classified definitely as a weakness from a system survival standpoint. That is, if a condition arose which threatened the system's existence, even though it had successfully encountered that condition previously, the storage search time might be so great that the system's existence terminated before it reacted favorably to the condition. The fourth feature is also a weakness of some importance, particularly with regards to concepts formed by the system. In particular, the system with unlimited storage and access ability would probably not form concepts but would continue only to store individual facts and not relate them to each other.

Thus one of the primary requirements to be placed upon any adaptive system would seem to be that of placing a limit on its storage capacity so that its method of adaptation to its environment will be fundamentally one of conceptualization and not of cataloging facts in unlimited storage.

Having now discussed some of the general qualities desired in an adaptive system, it now becomes necessary to consider ways and means of approaching the problem of design of this system. In this connection there are at least two different general philosophical methods which seem to be at the two extremes of adaptive design philosophy. One is the definition and determination of system goals and the resultant system synthesis using the definitions as guides. The other is the construction of a system using elementary components of extreme informational flexibility and the resultant analysis of that system. The former is the approach of going from the general system to the specific component whereas the latter is the approach of going from the general component to the specific system. Both approaches have advantages and disadvantages, some of which will now be discussed.

The first approach of establishing a goal and then building the system to meet the goal would seem to be, at first thought, rather desirable. Here the goal of adaptability is defined by the system designer, using any methods which are considered necessary to arrive at the definition. Then the designer goes about synthesizing the elementary components or other components which will ultimately be used by the system. Since the system's goal and operating procedure for obtaining that goal has been established, it would seem that the only problem facing the designer is one of synthesization. The synthesizing of the appropriate elements, however,--although somewhat established by physics and engineering--is certainly not a completely straightforward procedure and thus this method is not as simple as it appeared at first. In addition, there is a tremendously deceiving assumption in the method. That is that the system's goals can be apriorily decided so that the system will be adaptive. These goals are as yet unknown and so each system designed in this manner will be dependent upon the designer's use of information theory, logic, physiology, intuition, etc. Thus when the difficulty of synthesizing elements and the doubtfulness of the appropriateness of an apriorily chosen goal for an adaptive system are both considered, the previously seemingly logical method of solution is open to question.

Almost diametrically opposed to the approach just described is the second previously mentioned approach, that of designing extremely informationally flexible components and from these constructing specific systems. There is some reason to believe this method may be slightly more desirable than the former method, but some may take issue with this argument. For example, if the elementary components are made as flexible as the biological neurons then the existence of the biological system can be used as an existence proof that an adaptive system can be constructed from the flexible elementary components. Thus the system designer has first the problem of constructing elementary components which are considered to be as flexible as are the biological neurons of certain living organisms. Here he has the help of all the previous recorded research of the various pertinent biological sciences to aid in the determination of the flexibility required. Then he has the problem of assembling these components into various specific systems and then analyzing these systems to determine if they are adaptive. It would thus seem that once the elementary component requirements are established using the physiological neuron as a guide, it would be only a question of complexity of connectivity of these components to achieve an adaptive system.

However, there are also some subtleties of design involved in this approach that have not been mentioned. These are the establishment of the flexibilities required for the elementary components. It has been assumed that enough knowledge is presently available about the operation of the physiological neuron to make a choice of information handling requirements possible, but this may not be true. There may be certain features about the neuron which are not presently suspected which contribute appreciably to the functioning of the system. In the final analysis then, this latter approach also depends a good deal upon the designer's use of logic and intuition for its design. Thus it would seem that this method is also open to considerable question.

Therefore there appears no certain method of approach to the problem at present, but it is hoped that a combination of these two approaches will lead to a system which will exhibit adaptation to a limited degree. More about this will be stated in the next chapter along with the general specifications for the general elementary components to be considered. It is now of some interest to discuss some of the machines which have been constructed or contemplated.

3.2 Models

With respect to machines which have been constructed for the purpose of simulating some behavior characteristics of a biological system, only a few of the many will be described. These few seem, at present, to represent the most advanced models, and only two to be described have actually reached the physical existence stage of development, the remaining ones being partially constructed or simulated. When considered from the reference frame of an engineer or physicist, two of the machines seem rather simple and uninteresting, but when considered from the standpoint of psychology, their behavior is somewhat suggestive of animal behavior. That is, when the machines are considered with their basic elementary component operational laws fully understood, they may be considered uninteresting by some observers, but to individuals who do not have access to the basic units and their operation, the machines do indeed exhibit external behavior similar to animals. In a similar context, with the operational laws known only to a certain degree or accuracy--as is actually the case in all machines--then even to the physical scientist the operation of the machines hold an interest since they then become not wholly predictable but only statistically so. Thus the following machines are of interest to all observers because of the promise they hold forth for the development in the future of machines which are adaptive to their environment.

3.2.1 Machina Speculatrix

Machina speculatrix--or the tortoise as it is better known--was designed and built by Walter, an English physiologist, as an attempt to produce a model resembling an animal--at least in action, though not necessarily in appearance. By action is meant some measure of the following attributes of life as indicated by Walter:[37] exploration, curiosity, free-will in the sense of unpredictability, goal-seeking, self-regulation, avoidance of dilemmas, foresight, memory, learning, forgetting, association of ideas, form recognition, and the elements of social accommodation. Before describing the physiological accomplishments of the machine and its electronic circuit, a short qualitative description may be helpful.

The machine is constructed in such a shape as to remind one of a tortoise, hence its name. Figure 5* shows the general construction details. It is a three-wheeled battery-powered vehicle, the single front wheel

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* Reprinted with permission from P. de Latil, "Thinking by Machine," 1957, The Riverside Press, p. 50.

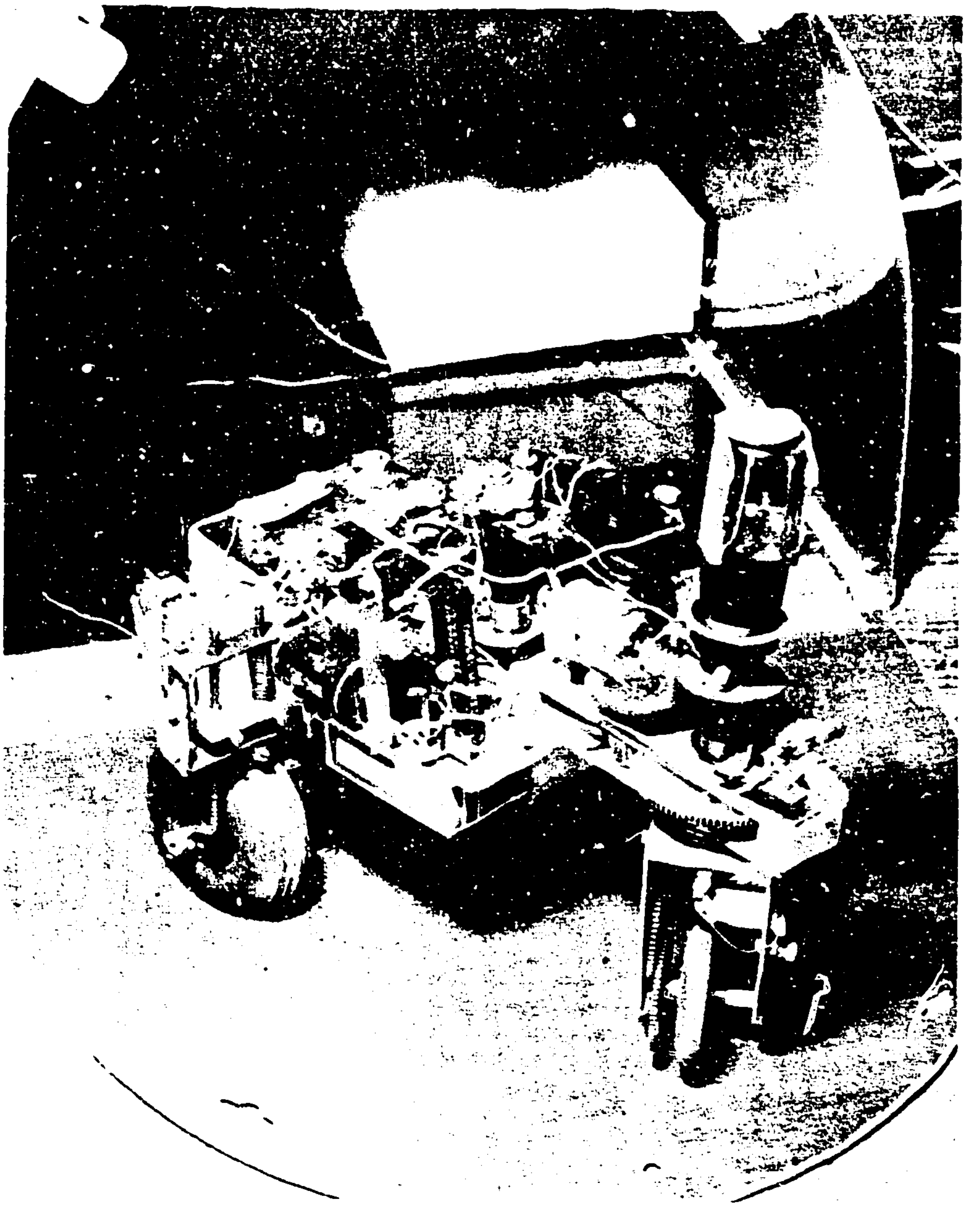


Figure 5. Walter's Machina Speculatrix

being the only driven wheel. This wheel is driven in two ways, one a traction drive which causes the wheel to rotate on its axis and thus move the tortoise, and the other a steering drive which causes the plane of the wheel to rotate about a vertical axis and so guide the tortoise. Both drives are from two separate electric motors which may be operated at two different speeds, depending upon the setting of their particular control relays. These relays are indirectly controlled by two receptors, one of which is a photo-electric cell and the other a limit switch attached to the hull of the tortoise. The photo-electric cell is mounted on the steering column of the front wheel so that the cell always faces in the same direction that the wheel is being driven. The steering motor runs continuously at full speed when no light is active on the photo cell, and so the photo cell scans an entire 360° steadily. When any light of moderate intensity enters the photo cell, the steering rotation and consequently the scanning, is stopped. When light of more than moderate intensity excites the photo cell, the steering motor runs at half speed. The driving motor is also controlled by the photo-electric cell, the result being that the driving motor operates at half speed when the cell is inactive and at full speed when the cell is activated by either moderate or intense light. The limit switch is forced closed when the tortoise hits something or when a slope is encountered. This connects the output of an internal photo-cell amplifier back to its input through a capacitor--the resulting connection forming a low frequency relaxation oscillator.

These oscillations alternately connect the steering motor on full and half power and the driving motor on half and full power respectively while also making the photo cell less sensitive to light. The over-all result of the closing of the limit switch is to produce a turn and push maneuver which is quite effective in getting around any objects which the tortoise may encounter.

The actions of the Mechina speculatrix are very suggestive of those of a restless animal. In the dark it wanders rather aimlessly, encountering objects and maneuvering around them. Any light of moderate intensity attracts it and it immediately moves in the direction of the light, again maneuvering around any objects in its path. It avoids an extremely bright light except when it is "hungry"--i.e. when its batteries are low in charge--at which time it makes all possible haste to the bright light. When the source of this bright light is the tortoise's hutch, it enters and makes the appropriate electrical connections automatically so that its batteries are recharged. When the batteries are fully charged, the tortoise backs from its hutch and proceeds to wander around its environment as before until its batteries are again low when it goes back to its hutch and repeats the charging cycle.

With regard to the physiological principles exemplified by Mechina speculatrix, the following are those which Walter claims for his creation:[37]

1. Parsimony is illustrated in the tortoise by its economy of structure, the machine containing two units corresponding to nerve cells--i.e. there are two vacuum tubes, two relays, two capacitors, two electric motors and two batteries. These two sensory detectors are affected by two sensory receptors, a photo-electric cell corresponding to a light receptor and a limit switch corresponding to a touch receptor.

2. Speculation is really the faculty which gives the tortoise its biological name and distinguishes it from some other machines. The machine is in a constant state of change and exploration. This is in opposition to the action of the Homeostat to be described later which only seeks a state of stability exhibited by lack of all action. Few machines, including computers, exhibit spontaneous investigation.

3. Positive tropism is exhibited by the tortoise's motion toward a moderately intense light. The beginning of this motion is immediate upon the reception of a light signal by the photo cell and since the steering motor is stopped by the light activating the photo cell, the movement toward the light is rather direct with few maneuvers.

4. Negative tropism, on the other hand, is exhibited by the avoidance of bright lights, obstacles, and hills. These avoidance maneuvers are all obtained by use of the same operational components used for positive tropism but automatically connected to function differently under the appropriate stimuli.

5. Discernment between effective and ineffective behavior is accomplished by the limit switch operation. Upon coming into contact with an object or encountering too steep a slope when it is moving towards a light, it immediately "forgets" the light and begins the task of avoiding the obstacles in its path, after which it again moves toward the light.

6. Optima rather than maxima conditions are sought. This is shown by the tortoise seeking moderate intensity lights but not bright lights.

7. Self-recognition by the tortoise is shown with the aid of a pilot lamp at the front which is lighted at all times other than when

the photo cell receives an adequate light signal. The light from the pilot lamp is sufficient so that when it is reflected from a mirror or white surface reasonably close to the tortoise, the photo cell is activated. This starts the machine moving toward its own reflection, but meanwhile the pilot lamp has been extinguished, thus stopping the motion toward the reflection. This process repeats with the over-all effect being one of an animal observing its own reflection and moving around in various positions before the reflecting surface.

8. Mutual recognition of two tortoises, attracted by each other's pilot lamp, appears as a result of an action on the part of each, similar to the self-recognition action above. That is, each is attracted to the other by the opposite pilot lamp, but when one sees the other's pilot lamp, it immediately turns off its own lamp. This removes its attractiveness to the other tortoise and the other tortoise begins to wander off. At this the first tortoise's lamp is again lighted and the other tortoise is again attracted. This process repeats indefinitely for both tortoises with the result that there appears an action similar to an animal's recognition of another of its species.

9. Internal stability is exhibited by the fact that a moderate intensity light attracts the Mechina speculatrix but a high intensity light repels it under normal conditions. However, when the batteries are low in charge, the internal stability is upset and moderation gives way to the desire for "food". Thus the Mechina speculatrix is attracted to a bright light. If this light happens to be the one in its hutch, then the batteries are recharged and Mechina speculatrix is revitalized. However,

if the bright light happens to be a fire, then the machine might very well be destroyed in its quest for "food".

About the operation and characteristics pertaining to self-recognition and mutual recognition of his tortoises, Walter has this to say.[37]

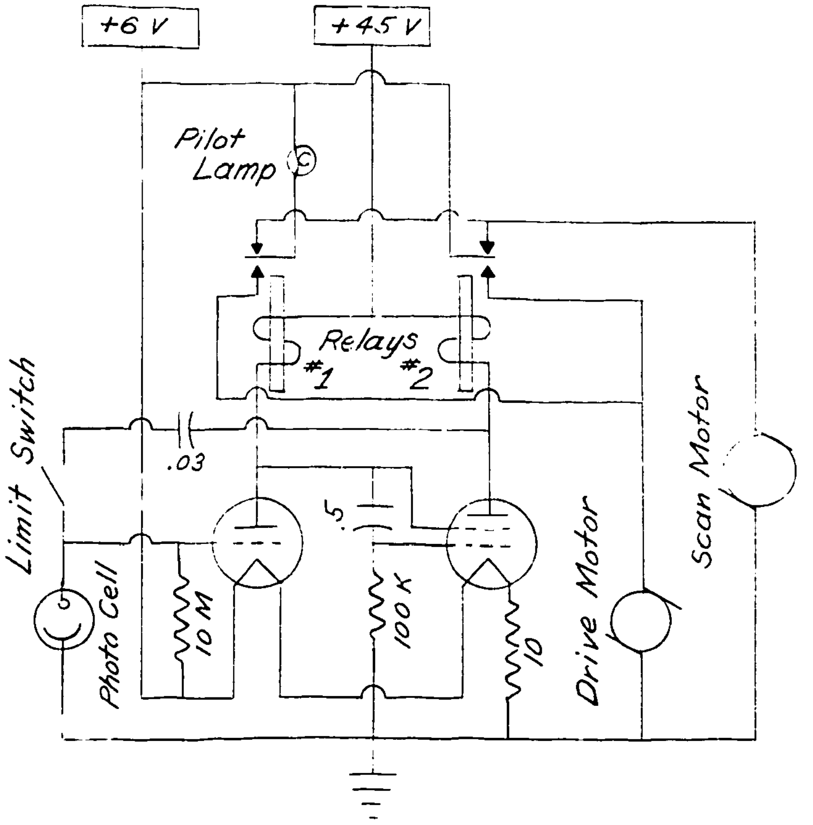
> "It may be objected that they are only 'tricks', but the behaviour in these modes is such that, were the models real animals, a biologist could quite legitimately claim it as evidence of true recognition of self and of others as a class. The important feature of the effect is the establishment of a feedback loop in which the environment is a component."

Figure 6 is a diagram of the electrical circuit of the Machina speculatrix. The diagram is self explanatory, any of the various modes of operation of the machine being fairly obvious once the circuit is studied. However, the mere simplicity of the circuit and the complexity of operation possible is one of the values of the automaton.

3.2.2 Homeostat

The aim of Ashby when he built the machine bearing the name Homeostat was to illustrate mechanically--i.e. in a non-living organism--the principle of homeostasis and particularly ultra-stability as he defines it. It is therefore useful to define these terms before discussing the machine itself.

Ashby uses the term homeostasis in the same sense as Cannon[7] and it means essentially the faculty possessed by a living organism to maintain



Resistance values in ohms
Capacitance values in microfarads

Figure 6. Circuit Diagram of Machina Speculatrix

itself in a relatively constant state of equilibrium. In particular, Ashby prefers to call this adaptation and defines it thus: [2] "... a form of behaviour is adaptive if it maintains the essential variables within physiological limits." The essential variables referred to by Ashby are in particular such variables in living animals as are closely related to survival such as pulse rate, blood pressure, body temperature, respiration rate, etc.

Ultrastability as used by Ashby is closely related to stability. Ashby's definition of stability is: [2] "Given an absolute system and a region within its field, a line of behaviour from a point within the region is stable if it never leaves the region." An absolute system is one whose line of behaviour in phase space from a phase point is always the same independent of how the system arrived at the phase point in question. For stability, then, the lines of behaviour of the system always remain within a region considered as the region of stability. The principle of ultrastability as stated by Ashby is [2] "An ultrastable system acts selectively towards the fields of the main variables, rejecting those that lead the representative point to a critical state but retaining those that do not." Thus the ultrastability criterion has the added feature over the stability criterion of requiring a change of phase space variables if the phase point is unstable. That is, ultrastability provides a means of stabilizing a point in phase space by selectively changing the range of the variables involved.

The machine built to illustrate ultrastability -i.e. the Homeostat -

consists of four identical units as shown in Figure 7[*] and diagramed in Figure 8. Each unit has a magnet pivoted about its center on top of the unit, the angular deviation of the magnet about its pivot point being the main variable. The output of each unit is an electric current whose amplitude and direction is proportional to the magnets deviation from its central rest position, the deviation being either positive or negative.

The deviation of the magnet determines this output current in the following manner: The magnet has attached to it a wire which dips into a trough of water. The trough of water has a potential gradient in it determined by electrodes at either end and is so placed that as the magnet pivots, the wire picks off a potential dependent upon the position of the magnet. This potential is fed to the grid of the triode (see Figure 8). When the potentiometer, E, is properly adjusted to gi zero output current for a central location of the magnet, then the deviation of the magnet will cause an output current, the direction and magnitude being dependent upon the magnet position.

The different units of the homeostat may be joined together so that each may influence the position of the other's magnet through the coils A, B, and C seen in Figure 8. D is a feedback coil from the unit itself. The magnitude and direction of these input currents to each unit's coils may be determined manually by the switches, X, and the potentiometers, P, at each coil.

When the units are connected together as described and the system is

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[*] Reprinted with permission from P. de Latil, "Thinking by Machine," 1957, The Riverside Press, p. 274

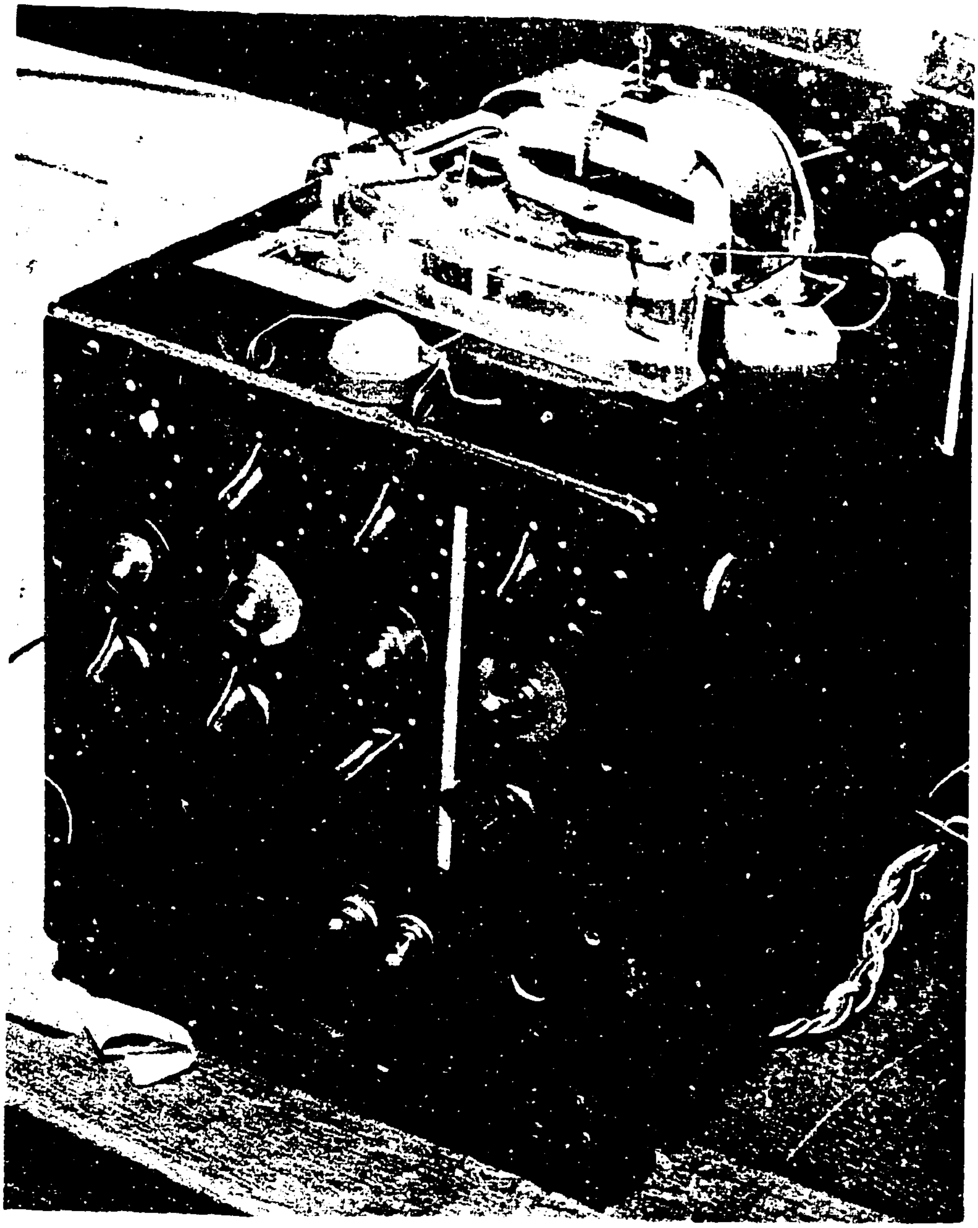


Figure 7. Ashby's Homeostat Unit

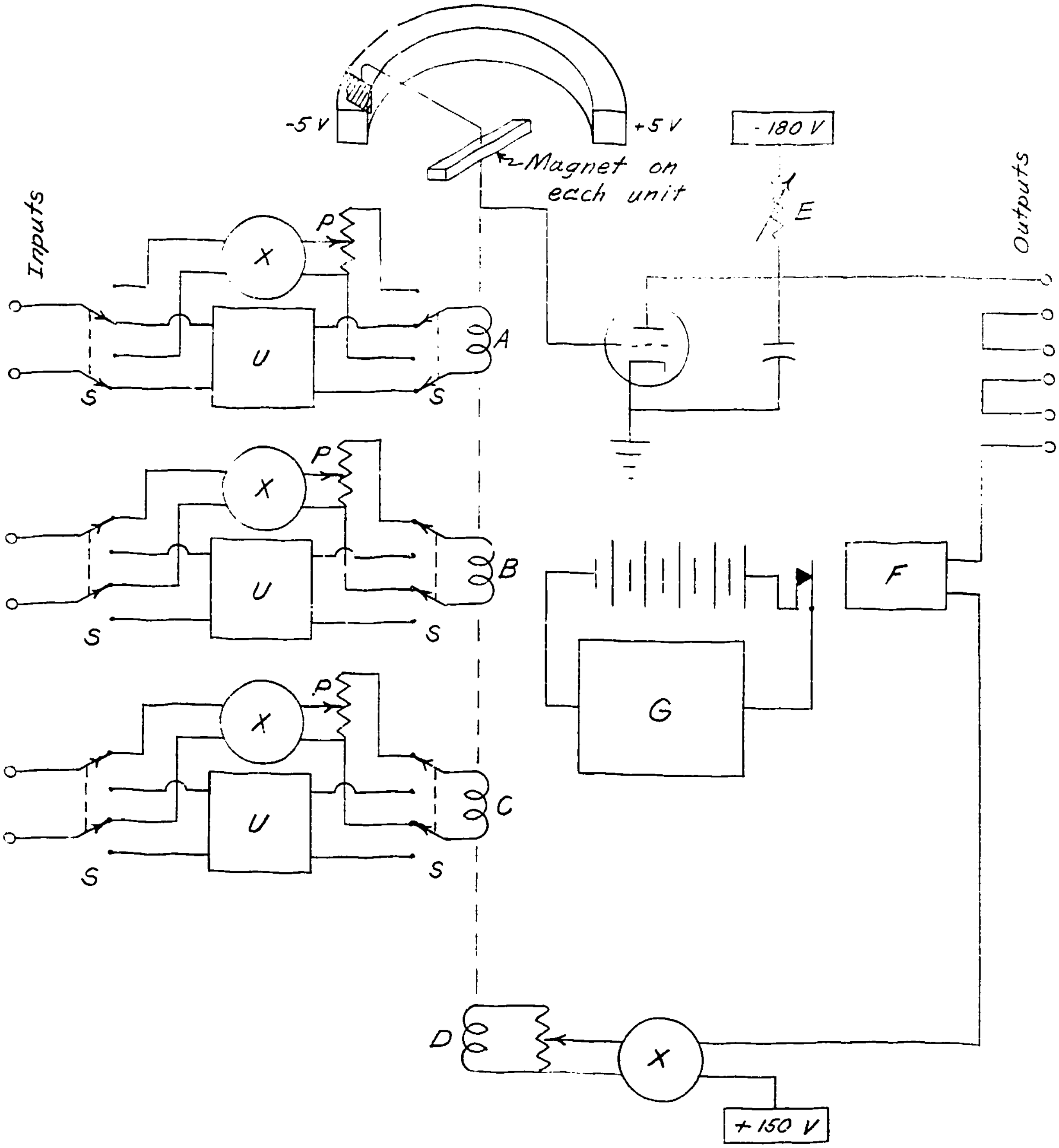


Figure 8. Circuit Diagram of Homeostat

energized, the magnets are influenced in such a manner that one of two things may happen. If the system finds itself in a region of the phase space where it is stable then the pattern of behaviour of the magnets is such that they move to the central position of their limits of movement and resist any attempt to displace them. If the system finds itself in a region of instability due to the switch and potentiometer settings, the pattern of behaviour of the magnets is such that the magnets diverge from their central positions resulting in a state known as unstable.

The system described above is a dynamic system of four variables whose phase space is determined by the switches, X, and the potentiometers, P. for a total of 32 parameters. For some parameter settings it is unstable and for others it is stable, but it is not ultrastable for any parameter settings.

If the switches, S, are set so that the inputs bypass the X's and P's and pass through the uniselector, U, then the system becomes ultrastable. In this new position of the switches, S, the values of the X and P parameters are determined by the uniselector, U. Each uniselector, consisting of all three U components on the diagram of Figure 8, is a stepping relay containing 25 positions. Thus there are 390, 625 combinations of input parameter values determined by the total of four uniselectors, one on each unit.

The uniselector coil, G, on each unit is energized only when sufficient current flows through the output and closes the relay, F. This occurs for a particular unit when its magnet diverges to a particular position in either direction from its central location --that is, when the system exhibits instability. As long as the magnet position is beyond this critical value, the uniselector will continue to change the input parameters. If the range of values of input parameters on each uniselector is sufficiently great, it is apparent that a combination of parameters--in fact many combinations--for all units exists which will stabilize the system.

The system just described now exhibits ultrastability and is the complete Homeostat. Any subsystem composed of one, two or three units joined together is also ultrastable and so also exhibits homeostasis. It should now be apparent how the ultrastable system differs from the stable system. The stable system contains parameters which are fixed and permanent in range with the result that the region of stability remains fixed. On the other hand, the parameters of an ultrastable system are variable in range so that the system's region of stability can be changed. Its operation consists of a set of transformations of the phase space until a region is found which is stable. When a distrubance takes the system out of the region of stability, the system transforms to a new region in phase space, ultimately ending in a new stable region. This is the entire goal of the Homeostat.

The Homeostat is an attempt to build a model of the survival equilibrium achieved by a living organism. It attempts to accomplish this by means of several independent units--each of which is stable in itself--reacting upon each other. The result is that achievement of equilibrium is exhibited by the Homeostat becoming insensitive to its environment and even resisting any attempt to displace the magnets from their resting position. Thus the Homeostat becomes dormant and uninterested when it has achieved its goal. This leads Walter[37] to conjecture that perhaps it is more like a plant than an animal.

3.2.3 Perceptron and Other Models

The two machines described thus far are physically existing machines and are rather simple in componentry and circuitry. On the other hand, the Perceptron, a machine designed by Rosenblatt[32] for the purpose of perceiving and classifying stimulus patterns active at its input, is not in existence. That is, as yet, it is in the stage of a theory of operation of a machine which has been simulated in a certain sense by a digital computer. The theory of the Perceptron is not based on simple components and circuitry, but upon rather complex units similar to biological neurons. In fact, the proposed operation of the Perceptron is very similar to the operation of the brain as proposed by Hayek[13].

The operation of the Perceptron is dependent upon the statistical connections possible between three basic types of units. The sensory units are transducers between the environment and the Perceptron. Their purpose is to code the various stimulus patterns into a form understandable by the association units of the Perceptron and to distribute this coded information amongst all the association units in a rather random manner. The association units are information digestive units which are so interconnected and so numerous in number that the result is a statistical analysis of the input information. When the results of these association unit's analysis are fed to the response units, which are the final units of the Perceptron, the overall response of the Perceptron becomes a function of the input stimulus patterns. Rosenblatt[32] shows mathematically that such a machine will statistically separate and classify environmental invariants after a training period. Implied in this theory is the fact that the number of units and their possible interconnections in the Perceptron is so great that detailed knowledge about them at any time is practically impossible. Therefore any ultimate understanding of the operation would have to be based upon some kind of a statistical analysis.

Pask takes a somewhat different but nevertheless a rather intriguing approach to the problem of adaptive organization. His philosophy seems to be that it is only relevant to study the interaction between two systems to decide whether either system is adaptive and to judge whether the over-all organization is meaningful. This philosophy is partly exemplified by some of his teaching machines, the punch card operator trainer being a typical example.[28]

This machine presents to the operator trainee a set of punch card symbols in a certain sequence and with a certain time interval between symbols. The operator in turn must punch a corresponding symbol on a keyboard after being presented a symbol by the teaching machine. The time required for each symbol presentation and corresponding operator response is recorded by the machine and this information is used to influence the machine's particular symbol sequence and time of symbol presentation in future exercises. Thus the machine paces the trainee's performance by setting a rate of operation dependent upon the trainee's past performance for a particular sequence of symbol presentations. In this way, the teaching machine continually examines the trainee's performance and attempts to correct deficiencies by appropriate adjustment of rate of operation. Thus the teaching machine and operator become a total system, each part adapting to the needs of the other in a particular functional manner. The result, to quote Pask is:[28] ".... that a teaching machine is something like an adaptable artificial limb, or an adaptable notebook, namely a piece of his surroundings which the trainee fashions and uses."

4. PROPOSED ADAPTIVE AUTOMATON

4.1 General Description

Having completed the description of two generally basic approaches to the problem of designing an automaton which will embody some of the behaviour characteristics of a biological system, and before stating what are believed to be the minimum requirements of any elementary components to be used in the construction of a general self-organizing sutomaton, a short qualitative description of the proposed automaton and its operation will now be given.

The automaton will be composed of many elementary components, customarily known as artificial neurons, which are all essentially alike functionally. These elementary components are connected to each other in a "very general manner"--to be explained later--such that the information flow between elementary components is through a variable conductance path called a facilitator. The conductance of the facilitator is time and use dependent. That is, the more a particular facilitator is used with respect to the total information transferred by it in a given time, the greater is the effect of that information upon the receiving elementary component.

The effect of the facilitator may be considered as a variable gain whose value is dependent upon the time integral of the information flow through it. Thus the gain of the facilitator is the ratio of the magnitude of the output energy of the facilitator to the input energy to the facilitator where both energies are those connected with the coded information being transferred through the facilitator--i.e. the signal energy.

As a result of the facilitators, preferred paths of information flow within the machine will be established, these paths being dependent upon the information content, its code, its source in the sense of its input location in the machine, and the total information stored or in transit within the machine. Thus the state of the automaton and its changes of state will be dependent upon the stimulus history of the machine.

For example, the automaton might be started at some given time with the initial conditions of the facilitators such that no connectivities were present between any of its elementary components. As the automaton received information from its environment in the form of stimuli patterns, either the same pattern or various patterns, paths of connectivity between the various particular input elementary components and the other elementary components of the automaton would be established and would increase in gain, thus facilitating the information transfer over particular paths. The establishment of the information paths and the information flowing through the automaton would constitute some activity within the automaton, and for a given input stimulus pattern, activity would result which was characteristic of that particular stimulus pattern.

The observations of these activity patterns by an observer who may be a set of "appropriate observation equipment" will constitute an output of the automaton. Since the response of the automaton is dependent upon the past history of the environment acting upon the automaton the response of the automaton to a given input pattern can be called an adaptive response.

If the "appropriate observation equipment" considered previously consists only of another large group of elementary components which are functionally like the elementary components used in the rest of the automaton, and if these "appropriate observation equipment" components are connected informationally to each other and to the automaton by means of facilitators, then the totality of automaton and observing automaton can be considered to be another automaton which can conceivably become self-recognizing.

The automaton with these facilities will then have a capability of "learning" since certain responses are characteristic of certain input stimuli and these responses in turn modify the existing states of the automaton. With a complete feedback loop from automaton "output" to automaton "input" through some "environment" - that is, with the addition of components which modify its environment which in turn will modify the automaton connectivity - - the automaton will have an adaptability to an environment different from itself.

With regard to the "very general manner" of connecting the elementary components, a comment may be made. Theoretically, a possible information path or facilitator could be connected between each elementary component and all other elementary components; in fact, many paths could be connected since these paths may be functionally different--for example, excitatory, inhibitory, threshold, etc. However, in practice, a laminar connectivity scheme will probably be used. This means that a number of elementary components are connected together to form a group of components and then several of these groups are in turn connected together in some sequential manner. It should be remembered that these connectivity paths are only possible facilitation paths, the actual final paths being determined by the pattern activity history of the automaton. The elementary component to be used in an automaton such as that which has just been briefly described can be qualitatively classified as a highly diversified data processor which utilizes the information present at its input in many different ways. For example, it is a summer, it is a storage unit, it is a correlator, it is a variable gain detector, and finally, it is a signal standardizer. These various functions will become clear when the specific requirements of the general elementary component are enumerated later. In this sense then, the adaptive automaton just qualitatively described is quite different from the general present computing machines since in the present computing machines, the various functions such as arithmetic, storage, input, output, control, etc. are localized in separate specialized portions of the machine whereas in the proposed adaptive automaton, functions corresponding to these are present in all the components and so are distributed throughout the automaton. That is, a standard computer compartmentalizes its function and a biological computer distributes, i.e. decompartmentalizes, its functions.

Now that a very qualitative description of a general adaptive automaton has been given, the specific requirements for the general elementary components to be used in the automaton will be stated and explained.

4.2 Elementary Component

As described in Chapter 2 of this thesis, physiological nervous systems use pulse code to transfer information when this information is of an immediate point-to-point type. By immediate point-to-point information is meant information which influences, and is being immediately processed by, various large sections of the system over reasonably short periods of time. This point-to-point, immediate effect information is of a short time nature as opposed to that of the regional, long time effects such as chemical stimulants, tranquilizers, metabolism, etc. The pulses which carry this short time, point-to-point, information are believed to be the only carriers of information associated with this particular effect. Therefore, the basic elementary components, also known as artificial neurons, will be designed to transmit and receive--process--information by means of pulses whose spacing in time vary. This type of modulation is known as pulse interval modulation.

The output of the elementary components will be pulses standardized shape and amplitude, the intervals between pulses being functionally related to the varied functional inputs of the particular elementary component. Each elementary component will have one output terminal to which many other elementary component input terminals may be connected, either by means of facilitators or directly. However, there will be many input terminals which have a large variety of functional effects upon the output of the elementary component. Thus the elementary component may be considered as a very flexible correlator whose transfer function will be dependent upon both spacial and temporal distribution of inputs from other elementary components.

Keeping in mind, then, the two general approaches to the problem of constructing a predictive model of a biological system in the sense of nervous behaviour characteristic and leaning very heavily upon the naturally given existence theorem as exemplified by the many biological systems in the present world, the minimum requirements of the elementary component to be used in the construction of an automaton, called an Adaptive Reorganizing Automaton, will now be enumerated.

1. The first requirement is that all information or data transmission which is of an immediate problem nature and is primarily point-to-point

will be by pulses which are basically pulse interval modulated. This requirement is primary because, as mentioned previously, it is generally accepted that the immediate flow of information in a physiological neuron net is by pulse interval modulation and it is the present desire to study artifacts resembling as closely as possible physiological systems. Another reason for pulse interval modulation is the realiability of detection and restandardization of pulses at points where information is processed, i.e. at the elementary components.

2. The output pulses from the elementary components will be standardized to a constant amplitude and pulse length. This requirement certainly follows the natural system as a guide for there seems to be no appreciable difference with respect to pulse shape and size between the pulses which originate at any one area of the cortex at various times or even between any area of the cortex and other areas either at the same time or different times, even though functionally the various regions of the cortex are quite different. In addition to using the physiological systems as a guide, technologically it is desirable to have the pulse output from each elementary component standardized. For example, modification of the pulse amplitude and width can then be reserved as operations to be performed at only certain points in the system which are under definite control and observation. Therefore, points of information or data control and reduction which may be monitored will be available in the automaton.

3. The greatest output pulse average repetition rate will not exceed 1000 to 1500 pulses per second. This is a rather arbitrary limit which is based partly upon similar limits found in physiological systems and partly upon the generally available instruments to be used for output or behavior determination of the complete automaton. For example, high speed photography of the operation

of the automaton--to be discussed later--would record and separate pulse rates in the range of about 500 to 1000 pulses per second.

4. The least output pulse average repetition rate will be not less than 10 to 15 pulses per second when the elementary component is actively correlating the input data present at its many input terminals. If the least average repetition rate becomes less than this rate, then an autonomous generator will act to trigger the elementary component and an output pulse will result. The lower limit of correlated pulse repetition rate is arbitrary as to actual value but it can not be zero, for with the existence of a lower limit of zero pulses output,--which means there is no pulse activity from a given elementary component--it is conceivable that the totality of elementary components in the automaton would become inactive, either due to a lack of stimuli of sufficient amplitude and intensity or due to a complete lack of stimuli. This inactivity is contrary to most biological systems since the generally accepted fact is that physiological neurons exhibit some pulse activity even when they are not stimulated at their inputs. This is apparently even true when the number of neurons considered is very small and isolated from neighboring neurons[6,10].

5. The duty cycle of the output pulses will be 30% or less when the pulse repetition rate is a maximum. This requirement is simply a close approximation to the physiological system.

6. When a given elementary component is stimulated at a constant input rate for a length of time, either all the inputs or any number of its inputs being stimulated at various individual constant rates, then the output pulse repetition rate will tend to decrease with time; that is, the elementary component will show signs of fatigue and lack of correlation with respect to

the input. The physiological systems show this tendency to a greater or lesser degree amongst the different species and also this tendency seems to be desirable so as to prevent saturation of any of the nets to the exclusion of other nets under prolonged fixed pattern stimulation. Without this property a biological system would show extreme attentiveness under certain stimuli patterns and indeed, undesirably, some individuals do have extended pattern fixation when subjected to certain stimuli for extended periods of time; for example, under certain fatigue conditions[10].

7. The output pulses of an elementary component will be essentially independent of the number of inputs to facilitators or to other elementary components which are connected to its output. Another manner of describing this requirement is that the output impedance of the elementary component will be small in comparison to the input impedance of the components which are connected to it. This prevents any "loading" effects upon the elementary component.

8. At least three functionally different types of input will be required for each elementary component correspondir to the electrical and the chemical inputs in a physiological neuron plus certain manual inputs to allow control of the elementary component by an observer for purposes of study and analysis of the artificial neuron nets. These inputs will give the elementary component extreme flexibility with respect to data processing which in turn will make the automaton more versatile.

The various inputs will be as follows:

a. Excitatory input with the various following attributes.

(1) Pulses which are active at the input and of amplitude great enough to raise the internal triggering energy above some excitatory threshold value (to be explained later) for

a time, δt, greater than about 25 microseconds, will cause the elementary component to produce a pulse at its output. Hereafter this act of producing a pulse by the elementary component will be spoken of as "firing".

(2) Two or more pulses at the input whose individual amplitudes are less than the excitatory threshold may be summed over a period of time, Δt, of about 0.25 millisecond to cause firing of the elementary component provided their sum is greater than the excitatory threshold value for the required time, δt.

(3) After firing, the elementary component will exhibit an absolute refractory time of about 0.5 millisecond during which time it cannot fire under any conditions. After this absolute refractory time it will experience a relative refractory time of several milliseconds during which time it becomes increasingly sensitive to input pulses.

(a') The conditions for excitation as stated above may be simply defined as follows: An elementary component will fire if the excitatory input energy causes the internal triggering energy to exceed a particular excitatory threshold energy. This requirement and the action of the elementary component corresponds quite closely to the functioning physiological neuron with respect to the excitatory input.

b. Inhibitory input with the following attributes.

(1) Pulses which are active at the input and of amplitude great enough to lower the internal triggering energy will prevent

or inhibit the elementary component from firing for a refractory period, $\Delta \tau$,--dependent upon input pulse amplitude--from the time of the input pulse. The gain of the inhibitory input section should be such that the effect of an identical pulse input to both the excitatory and inhibitory inputs simultaneously prevents the elementary component from firing.

(2) Two or more pulses at the input whose individual amplitudes would not affect the internal triggering energy may be summed over a period of time, $\Delta t'$, of about 0.25 millisecond to inhibit firing of the elementary component.

(b') The conditions for inhibition as stated above may be simply defined as follows: An elementary component will be inhibited from firing if the inhibitory input energy exceeds a particular inhibitory threshold energy. This requirement is very similar to the inhibitory action in a physiological neuron in that they are both essentially pulse by pulse inhibition.

c. Excitatory and inhibitory inputs simultaneously stimulating an elementary component will fire the elementary component only at those times when the excitatory pulse energies are greater instantaneously than the inhibitory pulse energies for a period of time which is dependent upon the relative magnitudes of the immediate past input pulse energies. This requirement is merely a result of the previous two requirements, a and b.

d. Threshold input with the following attributes.

(1) Pulse input threshold will have some of the characteristics of an excitatory or an inhibitory input depending upon the particular elementary component but with a much less effect per pulse and a much longer reaction time. This means, in effect, that many pulses from many other elementary components will be summed over long intervals of time and will thus establish some level of triggering energy which is not strongly influenced by individual pulses but is more a measure of activity of several interacting elementary components.

(2) Continuous input threshold will consist of fixed level transfer of triggering energy between elementary components This means that when two elementary components are connected through these terminals, the components average triggering energy levels at those points will be the same. These inputs then are bilateral in the sense that they are both inputs and outputs depending upon the particular direction of flow of data as contrasted to the pulse inputs of requirement d(1) which are unilateral, receiving data only. The continuous input thresholds correspond to the chemical thresholds of physiological neurons.

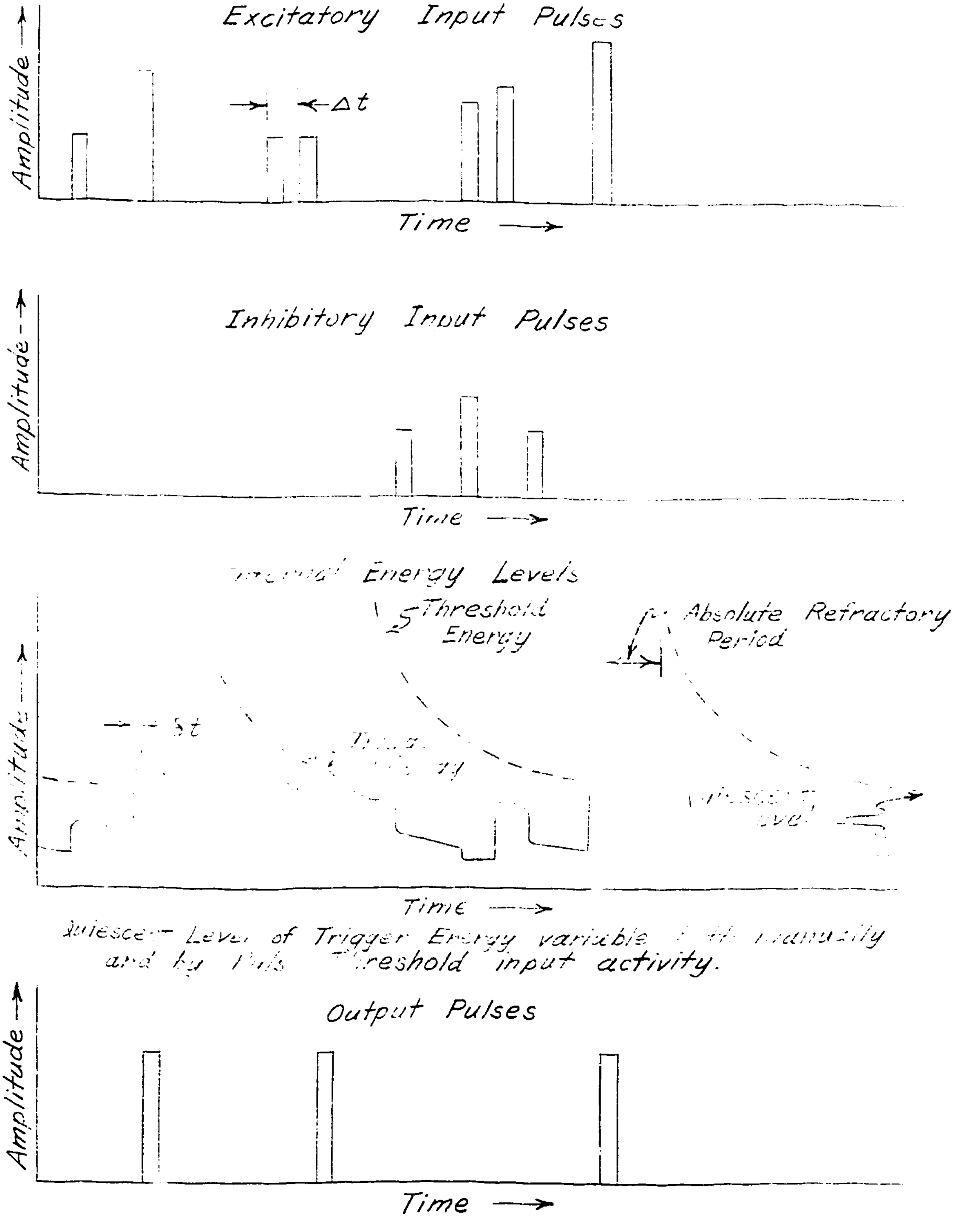
(3) Manual threshold will be simply an individual average triggering energy level control of the elementary component and amounts to an energy level control which desirably can be varied between limits which will either make the elementary

component autonomous at the high energy level or completely inoperative at the low energy level. The requirement of a manual threshold control is desirable from a research standpoint since it gives flexibility and controlability to the automaton. Quite obviously, there is no physiological neuron input which corresponds to this requirement.

The effects of various input pulses to the elementary component are summarized in Figure 9. The graphs of excitatory input pulses, inhibitory input pulses, internal energy level, and output pulses all versus time illustrate the operation of the elementary component very well. Particularly important in the understanding of the operation is the internal energy level diagram. On this is illustrated the fact that when the trigger energy curve and the threshold energy curve intersect and overlap for a time, δt, then an output pulse results. After this a period of absolute refractory time occurs, followed by a decay of the threshold toward the quiescent value. Also clearly shown are the effects of various amplitude pulses, both excitatory and inhibitory, upon the trigger energy level. It should be noted that for purposes of illustration varying amplitude input pulses have been used, but similar effects would result from varying pulse widths instead of amplitudes.

4.3 Facilitator

The Facilitator corresponds to the "bouton terminal" part of a physiological neuron as previously described. The "bouton terminal" is the adaptive section of the neuron in the sense of storage of information for long periods of time and adaptability to neighboring neuron environments, and thus is the plastic storage element in the cortex. Since it is intimately connected to the



Quiescent Level of Trigger Energy variable both manually and by Pulse Threshold input activity.

(Not to scale)

Figure 9. Control of Elementary Component by Various Input Pulses

neuron body or perikaryon, it is properly a part of the physiological neuron, but in the automaton proposed, the facilitator is a separate and self-existing component. This--as will be seen later--is desirable for purposes of flexibility of design and construction and also for purposes of flexibility with respect to the use of the automaton. The facilitator so conceived will give the automaton the ability to change its function with regard to its environment, both present and past. It is only by means of these malleable units which are here called facilitators that the automaton's behavior becomes a function of time and environment and thus can even be considered to have any adaptive features. Therefore the components representing the facilitators become the essential elements of the automaton. Keeping this in mind, the following are the requirements of any facilitator units.

1. The facilitator will modify either the amplitude, the length, or both, of the pulses which are active at particular inputs. This modification will be a function of the facilitator's information transmission rate and can be spoken of as the gain (gain is the same as that defined on the first page of this chapter) of the facilitator. This requirement is obvious since only these two parameters--namely, amplitude and pulse width--remain as variables in the pulse interval modulation code which has been adopted as the means of transferring information in the automaton.

2. At least three functionally different types of inputs will be desirable to provide flexible gain control of the facilitator. One of these corresponds to the physiological synapse while the other two will be used to determine the effects of both positive and negative facilitation in

the automaton. The inputs to any facilitator will be the following:

a. Positive facilitation will be a pulse input which has a transfer function--i.e. a gain--which is modified by the rate of information flow through the facilitator and by the time the facilitator has been in operation. That is, the gain, G, of a facilitator is a function of time, t, and the rate of information flow, dH/dt, as follows·

$$G = f\ (t, \frac{dH}{dt})$$

The positive facilitation will thus transfer a pulse from input to output after operating on the pulse with a gain, G. This gain will increase the energy content and consequently the effect of the pulse upon the elementary component as a result of the positive facilitation.

b. Negative facilitation will be a pulse input like the positive facilitation but with two different effects. It will decrease the energy content, and consequently the effect of a pulse upon the elementary component, and also there will be no transfer to the output of pulses active at the negative facilitation input--only pulses active at the positive facilitation input are transferred to the output with variable gain. This allows feedback from any point in the automaton to control a facilitator's gain without this control information interfering with the original transferred information.

An example of where this would be useful may clear up the details. Assume that the output of an elementary component is connected to the negative facilitation input of a facilitator whose output is connected directly to the elementary component in question. Then when the elementary component fired, the pulse would reduce the gain of the facilitator without interfering with the original information. This method of control of the gain of a facilitator offers one possibility for the prevention of saturation of the facilitator. This connection is shown in Figure 10.

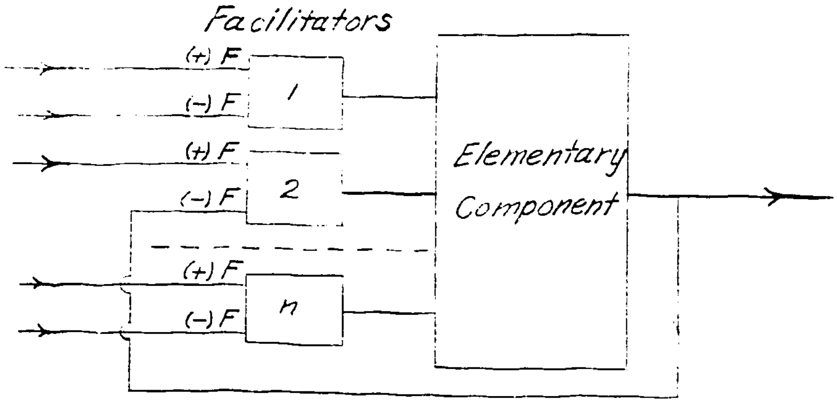


Figure 10. Illustration of Negative Facilitation Control of Facilitator 2.

With respect to the relative gain changes caused by the same pulse being active at both the positive facilitation and negative facilitation inputs, the effect of one input should exactly cancel the effect of the other, with any unbalance being in favor of the negative facilitation. Thus the gain of a facilitator can be controlled and prevented from saturating.

c. Manual facilitation input will be manual control of the gain of the facilitator. This will allow the gain of the facilitator to be set at any value from zero to maximum for either giving the automaton an arbitrarily determined memory, destroying part of its memory, or special analysis experiments.

3. The facilitator saturation time from zero gain will be about ten minutes. This means that the time required for the gain of the facilitator to change from zero value to maximum value should be about ten minutes when it is being excited continuously by pulses at its input which have a repetition rate of about 200 to 300 pulses per second. This requirement is an attempt to duplicate reasonably closely the action of a physiological synaptic junction although the data available are rather limited. McCulloch has suggested that the "learning time" of a natural neuron may be from two to twenty minutes, and so ten minutes seems to be a reasonable compromise.*

4. The facilitation decay time from maximum gain will be quite long, probably hours. Here again there is very little data available, so this time is at best a reliable guess.

The Facilitator output is shown in Figure 11 for various input pulses. The four graphs illustrate respectively various pulses at the positive facilitation input, various pulses at the negative facilitation input, the facilitator gain resulting from the inputs, and the output pulses from the facilitator. It will be noticed that output pulses only result when pulses are active at the positive facilitation input and are not present when the negative facilitation input alone is active. Also apparent from the facilitator gain curve is the decay of gain between pulses--for example ΔG for a given time Δt.

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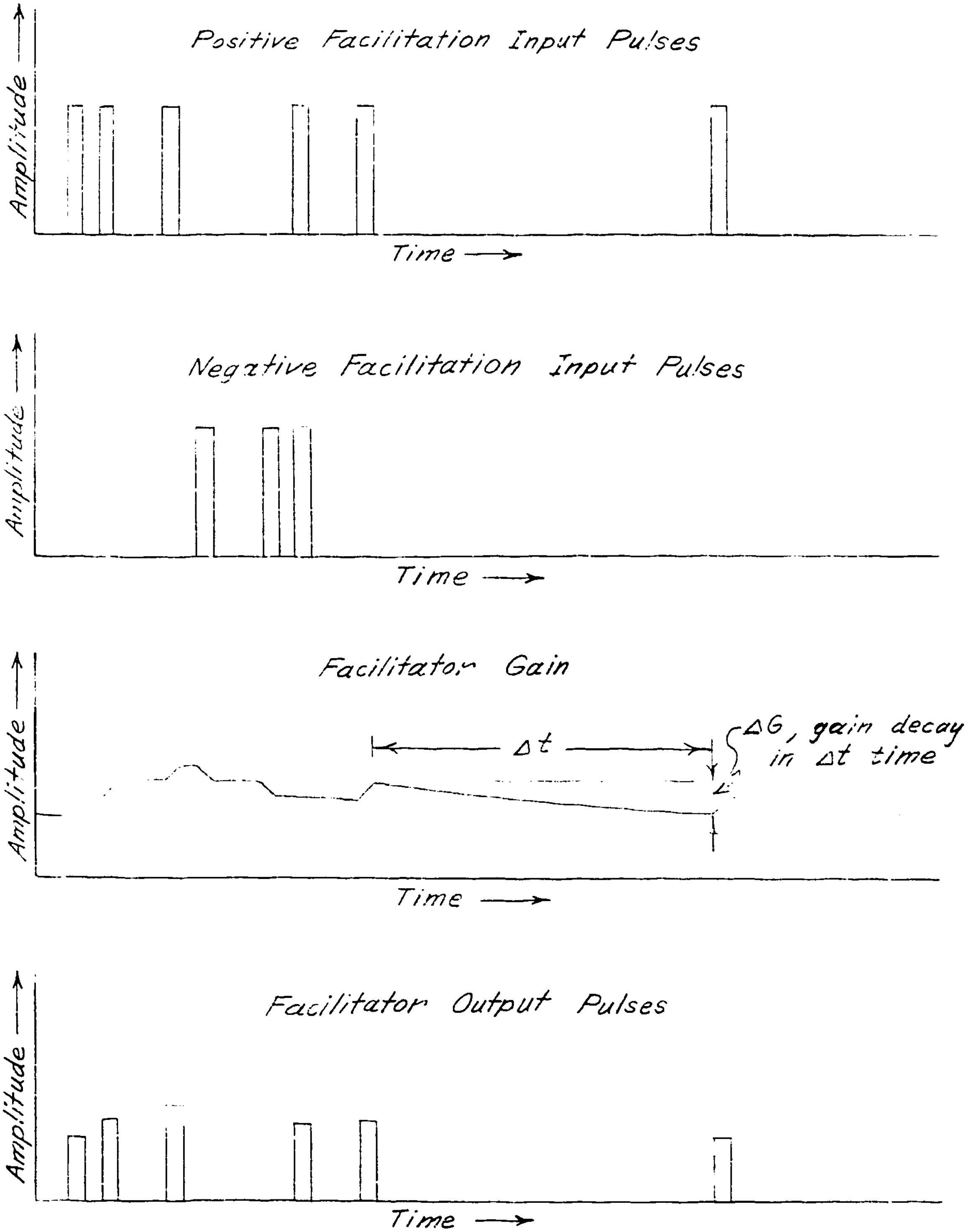
* Personal communication with McCulloch.



(Not to scale)

Figure 11. Control of Facilitator by Various Input Pulses

4.4 Automaton Assembly

Having specified the requirements for the various basic components to be used in the general adaptive automaton, the discussion can now be turned to the manner of assembly of these components. With respect to helpful hints from neurology as to the manner of assembly of the physiological neurons in a biological system, the data available are very limited and so are of little value, and thus neurology offers small help. However, since one of the purposes of the automaton is the study of the basic principles of operation of an adaptive system and particularly the study of the connectivities possible between artificial neurons, the following comments about the automaton assembly will be stated with these purposes in mind.

Probably the most important requirement with respect to the automaton assembly--and perhaps the only actual requirement--is that of instrumentation of the automaton. The problem of instrumentation of the general adaptive automaton must receive special attention and so will be discussed in a separate section. Therefore it is sufficient to state here that, with respect to the automaton assembly, adaquate consideration for the detection of the operation of the automaton must be given. That is, each component will require access terminals from which information about its operation and particular state may be obtained. Also the mode of connection of the various components must be such that information may be obtained about the connection as to location as well as about its pulse history. This means that the various paths of activity of information flow within the automaton, as previously indicated, can then be adequately observed and monitored.

There are other features which should be considered in the assembly. For example, the structure of the physical component so that it will be convenient to connect them together into any of many different systems. There is also the matter of data recording. Since the components will be connected together in many different ways to form different systems, some thought should be given to the geometrical placement and construction rigidity of the components so as to facilitate identification of the various units when studying the systems. These various points will be covered when the specific automaton is described.

In summary, then, all the specifications and comments about the general automaton assembly are for purposes of making the device functionally flexible so as to make it a good investigatory instrument.

4.5 Instrumentation of the General Adaptive Automaton

If the intents and purposes of the general adaptive automaton are to be fully realized, then the instrumentation of the device for detection of its operating states is extremely important. That is, one of the primary purposes of constructing any self-organizing automaton as an investigatory instrument is to study its behavior and operation, with the implied motive of learning as much about its principles of operation as possible. It is then obvious that the automaton must be as thoroughly instrumented as is practical. But with perhaps tens or hundreds and possibly thousands of elementary components in the automaton, it becomes quite apparent that the complete detailed operation or behavior becomes impractical to monitor and record. To do this would require far more equipment--even many times more--than the automaton itself contained, which is already appreciable considering the complexity of each elementary component and the facilitators connecting these components.

Therefore a compromise between the ideal situation of monitoring every detail of operation and the absurdity of monitoring nothing must be met.

The previous requirements of the automaton assembly indicated a necessity of obtaining information from each elementary component and facilitator during operation of the automaton. It is now apparent that this cannot be done in a simultaneous manner from all the components in a complex automation. However, it is possible to select relatively large groups of components, either spacially or topologically related in the automaton, and observe--i.e. monitor--their operation individually by means of some reasonably chosen methods of detection, these methods being dependent upon the particular type of automaton under study, such as chemical, electro-chemical, electrical, mechanical, etc.

For example, each automaton having been constructed by an individual or group of individuals, will be limited, in a certain manner, at each junction or information exchange point, as to its total number of variables possible. Perhaps the range of variables will not be known nor even all of the possible types of variables, but certainly, within limits, the creators of the automaton will know the variability of the automaton at the component level. The detection of the values of the variables then becomes only a matter of attempting to monitor each of the variables in the best manner possible for that particular variable under consideration. With this in mind, the following requirements for the monitoring and analysis of the operation of the proposed general adaptive automaton will be given. These requirements are considered minimal from the reference frame of the automaton's designers and thus seem to be sufficient requirements.

1. The input and output activity of any elementary component and its

immediately preceding facilitators will be measured by some type of indicating devices. This means that indicators of the type that show the presence or absence of pulses at the aforementioned points must be available in sufficient quantity to indicate the activity of either a single component or of any group of components whose number is not below about 10% of the total elements in the automaton. The 10% figure of desirability is presently arbitrary and can only be justified intuitively. These indicators must not "load" the automaton in any manner which interferes with its normal functioning and should indeed have no effect upon the operation of the automaton. Thus they may be removed and inserted at any point in the automaton and will be truly flexible indicators with respect to placement. The indicators so chosen should--perhaps with the aid of auxiliary equipment--be capable of indicating not only the presence of pulses but also the pulses' amplitudes and their placement in time relative to all other pulses being detected at various other points. These indicators will probably be at each location for reasonably long times; that is, for times longer than the transient times of the automaton being studied.

2. The transduction points between the automaton and its environment will be monitored. In general, there will be two types of transduction points, those that are considered as inputs to the automaton and those that are considered as outputs from the automaton. The types of equipment used to monitor these points will be the same generally as those used in requirement 1. However, the same flexibility with respect to topological placement is not required at the input and output because these points will be continuously monitored during the entire operation of the automaton. This applies particularly to the output, since here the instrumentation essentially is a

part of the output transducer from the automaton to its environemnt. With respect to the input, the monitoring instruments can be a part of the input transducer and so may be considered separately from the automaton. However, it seems more desirable to have both the input and output monitoring instruments as part of the general adaptive automaton equipment.

3. The third and probably the most important requirement of the instrumentation will be the measurement of any correlation between input activity and output activity. This means a method of recording simultaneously for a period of time the indications obtained in requirement 2. This correlation and its change as a function of time is one of the primary reasons for the construction of the automaton because this will reveal the degree of self-organization or adaptivity present in the automaton. This particular correlation requirement may be met in practice by the use of standard digital or analogue computers used as the correlation storage and measuring equipment in conjunction with properly designed transducers mapping from the adaptive automaton code to the digital or analogue computer code. However, this is getting into the specific instruments to be used, and so will be properly another part of this thesis.

5. FINAL DESIGN OF THE ADAPTIVE REORGANIZING AUTOMATON

5.1 General Comments

A general adaptive automaton has been described in the preceding chapter, along with some rather idealistic requirements for that automaton. Since the problem is now one of constructing a specific device, these specifications will serve as a guide in the final design specifications. The specific automaton, known as an Adaptive Reorganizing Automaton, is an attempt to build a system which will exhibit a minimal number of behavior characteristics of a biological system. Its purpose will be mostly investigatory in nature and so an attempt will be made to meet as many of the ideal specifications as possible.

When the requirements stated in the previous chapter are carefully considered, it soon becomes apparent that they are the specifications of a device which is functionally very flexible. That is, the requirements of the automaton are such that, if they are all met, it surely seems that the system may be flexible enough functionally to meet its proposed purpose. Therefore, since the requirements are rather varied, it would perhaps seem to be advisable to use techniques taken from many different fields of science for the final design. For example, the information carrier energy could be based upon electronic designs, the control sections of the components could be perhaps electrical or chenical, the storage sections of the units could be chemical or mechanical apparatus, etc. These various types of apparatus would then be joined together with the appropriate transducers between them, thus completing the system.

These were some of the thoughts when the design was started. After exploring some of the various chemical and mechanical approaches to the design of different functional units, it became apparent that if the basic automaton signal energy was to be of an electrical origin--and this fact was accepted because the existing techniques of electronic engineering are very well suited to the requirements of the signal energy--then it would be much simpler and more expedient to make the entire system an electronic one rather than to mix chemical, mechanical, and electrical components, with the associated necessary transducers, into one system. Also, the all electronic system offered certain advantages with respect to the availability of component parts and the required assembly procedures. Therefore, the design of the first model of the Adaptive Reorganizing Automaton solidified into a completely electronic design.

Having thus decided to construct an electrical adaptive automaton, the decision was next made to use solid state devices as much as practical. This was based upon the fact that for the large number of elements involved in the construction of even a rather limited automaton, the presence of tubes and their associated heat dissipation in the heaters becomes somewhat undesirable. Also, since the levels of operation are low both in frequency and amplitude, and the fact that operation is by pulse techniques, the use of transistors seems almost ideally suited to the construction. This requirement was satisfied to a limited extent but unfortunately could not be completely met economically--but this will be explained later.

The most important practical problem to be considered when the construction of the Adaptive Reorganizing Automaton was undertaken was the cost per unit since this cost was what ultimately determined the total complexity of the device. Therefore, the components which are described later are definitely compromises, with the complexity desired for each component somewhat relaxed so that a reasonable number of total components could be built and operated.

Once the over-all requirements mentioned had been chosen, the immediate question of component design was considered. The question as to how complex an individual component should be was an important part of that consideration. For example, an individually very complex component could be constructed which contained all the essential functions of the ideal elementary component and its associated facilitators and then the automaton would consist of only these components in different arrays connectivity. The connectivities between components then would be simply wires. This approach could be made to have as much ultimate flexibility with respect to connections as any approach but would be less economical because in many of the individual components all the possible connections to and from it would not be utilized and for particular experiments would not be wanted. Thus considerable duplication of sections of components would result. Another important deficiency of this method of design is the difficulty of modification of the automaton by additions to it of other diversified units. That is, if it was decided to add a unit other than between the presently existing components, the components themselves would require modification; and since the present Adaptive Reorganizing Automaton is the first model to be built, this deficiency could be serious in the future use of the automaton.

Almost diametrically opposed to the extremely flexible and complex functional component approach to the automaton component solution is the diversified component approach finally adapted in the design of the first Adaptive Reorganizing Automaton. This design consists of several flexible and functionally different components, each component type having some of the requirements of the previously mentioned very complex component and each component type being compatible with all the others so that they may be connected together by means of wires in many different configurations. Under certain connection conditions a group of these components would then have the same flexibility and function as one of the very complex components.

For example, the Elementary Component was divided into three functionally different units. These are two Energy Transducer units and an Autonomous Component unit. These units will soon be fully described, so it is sufficient to state now that by separating the very complex Elementary Component into much simpler units, it was possible to achieve units which are fairly simple in operation, but whose possible interconnections make for a very flexible automaton. Therefore this design has the advantages of the previous proposed design plus many other qualities which were considered important, such as minimum duplication of component functions for economy of construction, minimal component function for greater ultimate diversification of automaton experimental use, less technical skill required for construction and maintenance, and greater flexibility of component additions to the automaton for future experiments, both anticipated and not yet anticipated.

The rest of this chapter will be devoted to the functional description of each of the components used in the Adaptive Reorganizing Automaton. The circuit diagrams of these components will be found in the Appendix along with an explanation of the electronic operation of each. A discussion as to the various possible connections and the detection of operating details will be given in a later chapter.

A comment about the nomenclature to be used is now in order. All input and output signals from the various components will be considered as pulses unless otherwise specifically noted. All pulses will be of the same length denoted as standard and their amplitudes will be given by a ratio relative to the standard pulse amplitude denoted as unity or 1. Thus every pulse is normalized to the standard pulse. The symbol W will denote an instantaneous potential output level, pulse or otherwise, and the symbol Z will similarly denote an input. These symbols will be subscripted by other symbols, the first indicating the unit of the general component which is the source or sink as the case may be, the second indicating the general component from which the particular signal is arriving, and the third indicating the general component to which the signal is going. For example, W_{xjk} would be a pulse output of given amplitude from the X unit of the j'th general component and going to the k'th general component--i.e. it is the input to a unit associated with the k'th general component. All the values for W or Z are instantaneous potentials above the common reference point, ground. A general component as used here is an assembly of units which together will have most of the attributes of an ideal Elementary Component as described previously. That is, an Energy Transducer with its associated Facilitators and Autonomous Component would constitute a general component. Thus a general component is essentially an artificial neuron. It is also to be understood that there is a time delay, δt, between the arrival of any triggering energy into an output unit and the resulting output pulse. This applies particularly to the Energy Transducer to be described later. δt is a function of trigger pulse amplitude and of continuous input threshold base amplitude to be described later in detail with the description of the Energy Transducer.

[illegible].2 Energy Transducer

The Energy Transducer is the part of the Adaptive Reorganizing Automaton which contains some of the functions of the biological neuron cell body. Its function is the assimilation of information arriving at its inputs from many different sources within the automaton. For this purpose, there are two main functional sections, the pulse unit and the summer unit as shown in the block diagram of Figure 12.

The pulse unit is the immediate output unit of the Energy Transducer and is nothing more than a pulse standardization circuit which produces a standard output pulse whenever the input potential is above some threshold level, Θ_x, for a minimum given length of time. Therefore the X unit has a transfer function as follows: (Refer to Figure 12)

$$
\begin{aligned}
W_{xjk} &= 1 \quad \text{when} \quad Z_{xjj} > \Theta_x \quad \text{for a length of time} > \delta t \\
&= 0 \quad \text{when} \quad Z_{xjj} \quad \text{does not satisfy above condition.}
\end{aligned}
\qquad (1)
$$

where:

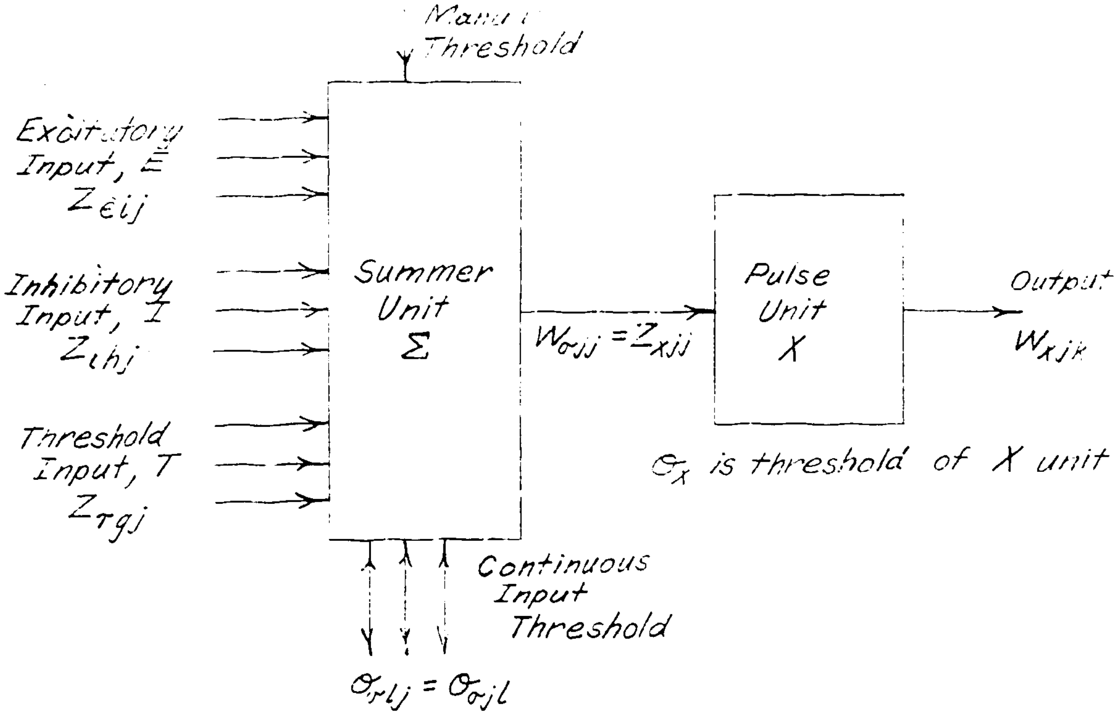
W_{xjk} is the instantaneous output potential of the X unit (always a standard pulse output).

Z_{xjj} is the instantaneous input potential of the X unit, also the instantaneous potential value of the output of the summer unit to be described later.

Θ_x is the threshold potential value of the X unit which determines firing of the unit.

δt is the minimum length of time required for the input potential to exceed Θ_x to cause an output pulse. This δt is not a constant but is somewhat dependent upon the magnitude of Z_{xjj} above Θ_x, and is also dependent upon the immediate past history of the X unit.

The summer unit is the control unit of the Energy Transducer in the sense that it determines the level of the instantaneous input potential to the pulse unit. The functional operation of the summer is qualitatively described as



Some Typical Identities

$Z_{\epsilon ij} = W_{\nu ij}$ and/or $W_{\chi ij}$ i variable and multi-valued

$Z_{\iota hj} = W_{\nu hj}$ and/or $W_{\chi hj}$ h variable and multi-valued

$Z_{\tau gj} = W_{\nu gj}$ and/or $W_{\chi gj}$ g variable and multi-valued

$W_{\chi jk} = Z_{\gamma^+ k\ell}$ and/or $Z_{\gamma^- k\ell}$ and/or $Z_{\epsilon k\ell}$ and/or

$Z_{\iota k\ell}$ and/or $Z_{\tau k\ell}$ ℓ variable and multi-valued

Autonomous Component Not Included

Figure 12. Energy Transducer Block Diagram

follows. The manual threshold input is a manual control which establishes a fixed potential component of the Σ output potential. The continuous input threshold is a direct current input which adds a varying potential component to the Σ output potential, the rate of variation being rather slow. No pulse variations are present in this input. This input is also the only input which is bidirectional, being either an input or an output under different conditions. The threshold input is a pulse input which also adds--or subtracts depending upon the particular Energy Transducer--a varying potential component to the Σ output potential, the rate of variation being somewhat greater than the continuous input threshold but definitely not of a pulse by pulse nature. That is, this input integrates the input pulses over a time interval many times greater than the average interval between pulses. The excitatory input is a pulse input which adds a pulse potential component to the Σ output potential, the rate of variation being practically the same as that of the pulse input with an input pulse integration over a time interval only a part of the average interval between pulses. This allows two pulses arriving at slightly different times to be summed. The inhibitory input is a pulse input which performs in a manner similar to the excitatory input but which subtracts a pulse potential component from the Σ output potential instead of adding a pulse potential and which also has an equal or greater absolute gain than does the excitatory input. Thus the transfer function of the Σ unit is the following.

$$W_{\sigma jj} = \Theta_j + \sum_{\ell} k_{\ell} \Theta_{\sigma \ell j} \pm \int_{t \gg \bar{T}} \Big(\sum_{g} k_g Z_{\tau g j}\Big) dt + \int_{t < \bar{T}} \Big(\sum_{i} k_i Z_{\epsilon i j}\Big) dt - \int_{t < \bar{T}} \Big(\sum_{h} k_h Z_{\iota h j}\Big) dt \qquad (2)$$

where:

$W_{\sigma jj}$ is the output of the Σ unit (not a pulse but a unidirectional varying potential).

θ_j is the value of potential established manually.

k_ℓ, k_p, k_i, and k_h are constants of their respective networks.

$\Theta_{O\ell j}$ is the value of potential at the respective continuous input threshold inputs.

Z_{Tgj} is the instantaneous value of the pulse amplitude at the respective threshold input.

$Z_{\epsilon ij}$ is the instantaneous value of the pulse amplitude at the respective excitatory input.

$Z_{\iota hj}$ is the instantaneous value of the pulse amplitude at the respective inhibitory input.

$\overline{T}$ is the average time between pulses.

$(\pm)$ in the pulse threshold term is either an additive or a subtractive term described later in the text.

$t >> \overline{T}$ means the integral is over the preceding time interval many times greater than the average pulse interval.

$t < \overline{T}$ means the integral is over the preceding time interval much less than the average pulse interval.

Note that the integrals above serve not only as pulse counters but also produce a potential which varies as the amplitude of the pulses counted. That is, the integral gives a potential which is both a function of the number of pulses and the amplitude of the pulses. This is necessary because at various points in the circuits being considered, information is present both as amplitude and number of pulses and so the integral notation is correct. Any discrepency which might seem apparent dimensionally is corrected by the appropriate constants.

Upon setting $W_{\sigma jj} = Z_{\chi jj}$ as indicated in Figure 12, Equations (1) and (2) combined become the transfer function of the entire Energy Transducer. Thus

$$\begin{aligned} W_{\chi jk} &= 1 \quad \text{when} \quad Z_{\chi jj} > \Theta_{\chi} \quad \text{for a time} > \delta t \\ &= 0 \quad \text{when} \quad Z_{\chi jj} < \Theta_{\chi} \end{aligned} \tag{3}$$

with:

$$Z_{\chi jj} = \Theta_j + \sum_{\ell} k_{\ell} \Theta_{\sigma \ell j} \pm \int_{t>>\overline{T}} (\sum_g k_g Z_{\tau g i}) dt + \int_{t<\overline{T}} (\sum_i k_i Z_{\epsilon i j}) dt - \int_{t<\overline{T}} (\sum_h k_h Z_{\iota h j}) dt$$

The circuit, which is fully described in Appendix A, is such that certain limitations and operating conditions are present. For example, immediately following an output pulse, an absolute refractory time of about 0.25 milliseconds exists during which no input energy can cause the elementary component to fire. After that a relative refractory period of 2 to 3 milliseconds exists These times are somewhat adjustable by means of the manual control. Thus the upper output pulse repetition rate is limited to about 1200 to 1500 pulses per second.

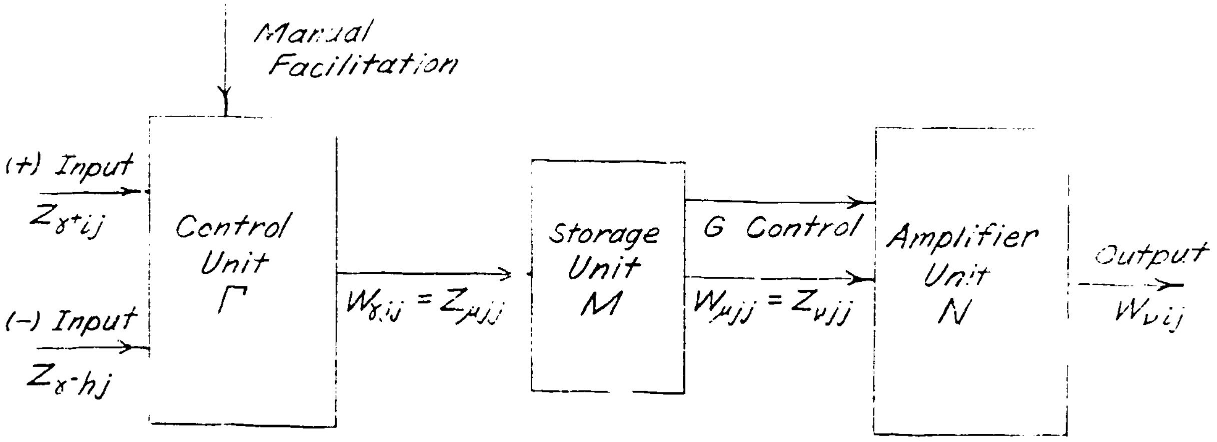
The pulse threshold input, as indicated, is of two types, being additive for some elementary components and subtractive for others. The additive threshold elementary components cause the output potential level of the Σ unit to increase as the average input pulse repetition rate at the threshold input increases, whereas, in the subtractive threshold elementary components, the output potential level of the Σ unit decreases as the average input pulse repetition rate at the threshold input increases. These two conditions correspond somewhat to positive and negative feedback and so they seem to be desirable for a general automaton since either may be desired under certain operating conditions.

The general functional operation is similar to the ideal situation depicted in Figure 9 of the previous chapter.

5.3 Facilitator

The design of the facilitation component part of the Adaptive Reorganizing Automaton presented the greatest challenge of any component used in the device. What was needed was a variable conductance unit, i.e. a malleable unit, which would vary in such a manner as to increase the ability of information to flow over a path between two points when that path was used more than other paths and also a unit which remembered or stored this use information--not the information transferred--for an appreciable time, perhaps hours. This malleable unit is the crux of the self-organizing system because it is the element which gives the automaton adaptability in the sense of reaction with its environment which changes with previous activity knowledge. The facilitation unit corresponds somewhat, therefore, to the biological neuron synapse. The resulting design is shown functionally in Figure 13 and the electronic diagram and the operation are described in Appendix B.

The output part of the facilitator is the amplifier unit which is a variable gain direct coupled amplifier whose gain is controlled by the storage unit to be described soon. The transfer function of the N unit is:



Some Typical Identities

$$Z_{\gamma^+ ij} = W_{\chi ij}$$

$$Z_{\gamma^- hj} = W_{\chi hj}$$

$W_{\nu ij} = Z_{\epsilon ij}$ and/or $Z_{\iota ij}$ and/or $Z_{\tau ij}$

Autonomous Component Not Included

Figure 13. Facilitator Block Diagram

$$W_{\nu ij} = -GZ_{\nu jj} \quad \text{when} \quad Z_{\nu jj} < 0$$

$$= 0 \quad \text{when} \quad Z_{\nu jj} \geq 0 \tag{4}$$

where:

$W_{\nu ij}$ is the instantaneous output potential of the N unit (always a pulse output).

G is the numerical gain of the N unit and is a function of the total number of pulses active for a length of time at the input of the facilitator (this will be described later).

$Z_{\nu jj}$ is the instantaneous input potential of the N unit (always a pulse input).

The storage unit stores information relative to the total number of pulses active over a length of time at the input to the facilitator. Essentially it is a pulse counter which takes its control energy from the pulses which are transferred through it so that the transfer function of the M unit is:

$$W_{\mu jj} = k_{\mu} Z_{\mu jj} \tag{5}$$

where:

$W_{\mu jj}$ is the instantaneous output potential of the M unit (always a pulse output.)

k_{μ} is a constant for any particular M unit.

$Z_{\mu jj}$ is the instantaneous input potential of the M unit (always pulse input).

The control unit consists basically of two direct-coupled amplifiers, one of which is a phase inverter. The output of these two amplifiers is summed to become the output pulse of the Γ unit. When the output pulse is the result of only an input pulse at the (+) facilitation input, the storage unit, M, stores a positive charge and the gain, G, of the amplifier unit, N, is increased a given amount, △ G. When the output pulse is the result of only an input pulse at the (-) facilitation input, the storage unit stores a negative charge and the gain of the amplifier unit is decreased an amount, △ G′. Thus the transfer function of the Γ unit is.

$$W_{\gamma jj} = -k_{\gamma^+} Z_{\gamma^+ ij} + k_{\gamma^-} Z_{\gamma^- hj} \qquad (6)$$

where:

$W_{\gamma jj}$ is the instantaneous output potential of the Γ unit (either a positive or a negative pulse.)

k_{γ^+}, k_{γ^-} are constants of their respective networks.

$Z_{\gamma^+ ij}$ is the instantaneous input potential of the (+) facilitation input (usually, but not always, a standard pulse).

$Z_{\gamma^- hj}$ is the instantaneous input potential of the (-) facilitation input (usually but not always, a standard pulse).

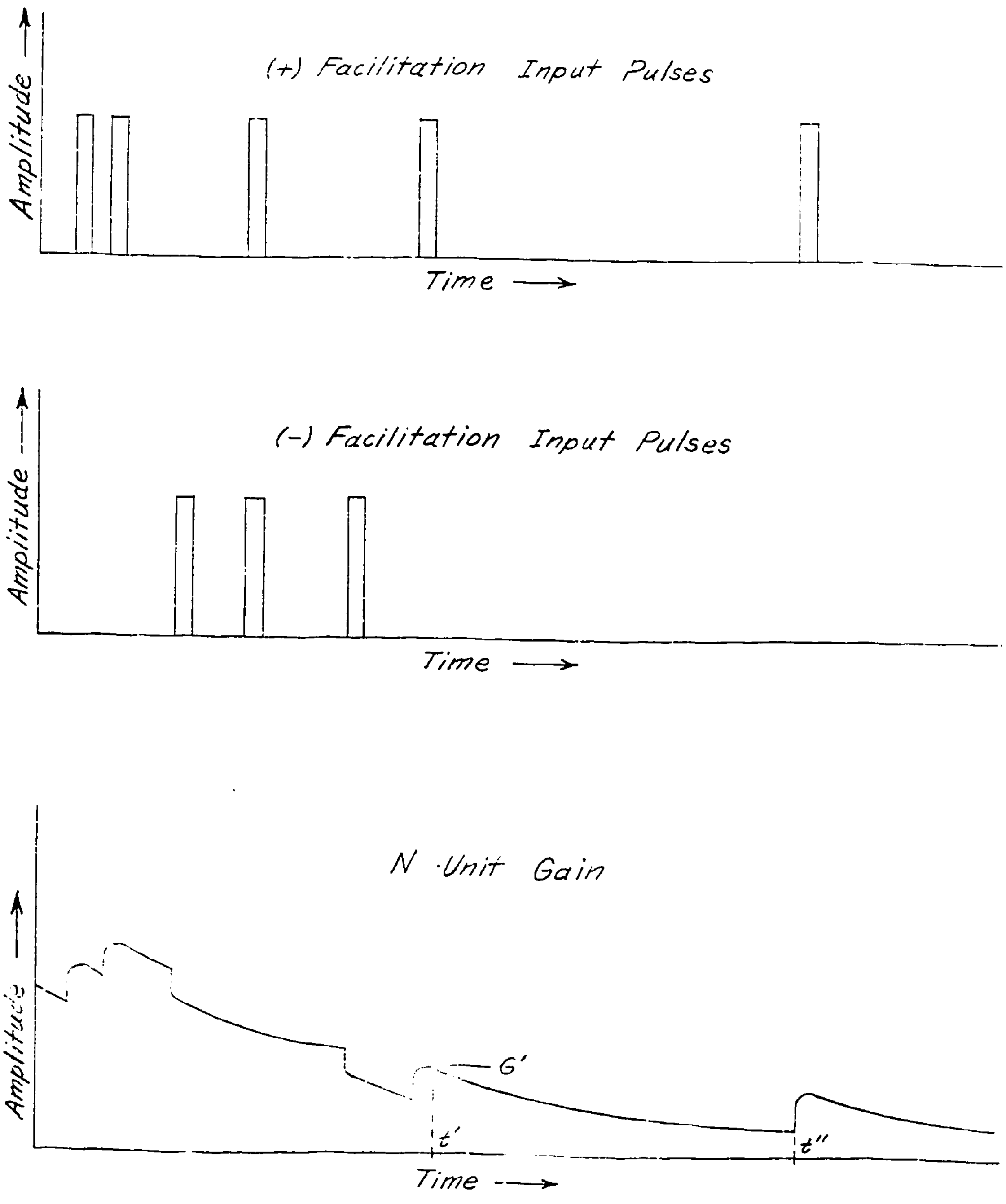
In addition, the control unit indirectly controls the gain, G, of the N unit with the result as shown in Figure 14. The gain resulting may then be expressed as:

$$G = k_{\nu} \int_{t} W_{\gamma jj} \, dt + \sum_{t} \text{(exponential decay terms)} \qquad (7)$$

where:

G is the instantaneous numerical gain of the N unit.

k_{ν} is a constant of the respective network.



(Not to scale)

Figure 14. Gain Function for N Unit

$\int_t$ is an integral taken over the period of time from the immediately preceding instant of zero gain to the present.

$\sum_t$ means summing of the exponential terms encountered sequentially in time.

The exponential decay terms are the "leakage" terms and are simply written between jumps in the gain curve as:

$$G = G'\epsilon^{-\frac{t-t'}{k}} \qquad t' < t < t'' \tag{8}$$

where:

G' is the instantaneous gain at time, t'.

t is any time such that $t' < t < t''$.

$t''-t'$ is the time interval over which the expression is true.

k is the decay time constant of the storage unit and associated circuit.

Upon setting $W_{\mu jj} = Z_{\nu jj}$ and $W_{\gamma jj} = Z_{\mu jj}$ as indicated in Figure 13 Equations (4), (5), (6) and (7) become the transfer function of the entire facilitator component. That is:

$$\begin{aligned} W_{\nu ij} &= -Gk_{\mu}(k_{\gamma^-}Z_{\gamma^-hj} - k_{\gamma^+}Z_{\gamma^+ij}) \quad \text{when} \quad (k_{\gamma^-}Z_{\gamma^-hj} - k_{\gamma^+}Z_{\gamma^+ij}) < 0 \\ W_{\nu ij} &= 0 \qquad \text{when} \qquad (k_{\gamma^-}Z_{\gamma^-hj} - k_{\gamma^+}Z_{\gamma^+ij}) \geq 0 \end{aligned} \tag{9}$$

where:

$$G = k_{\nu}\int_t (k_{\gamma^-}Z_{\gamma^-hj} - k_{\gamma^+}Z_{\gamma^+ij})dt + \sum_t G'\epsilon^{-\frac{t-t'}{k}}$$

when $G'\epsilon^{-\frac{t-t'}{k}}$ is chosen properly as indicated in Figure 14, by letting G' be the gain G on the immediately preceding jump in the gain curve.

The facilitator circuit has several unique features as described in Appendix B. For example, the storage unit may be changed readily to give an extremely wide range of adaptation times from seconds to hours; similarly for the decay times, if other than capacitors are considered--for example, nickel-cadmium batteries.

It should be remembered that only pulses active at the (+) facilitation input are amplified and appear at the output of the facilitator with an over-all gain ranging from zero to two. Pulses active at the (-) facilitation unit are not amplified, but are used only as control of gain.

5.4 Autonomous Component

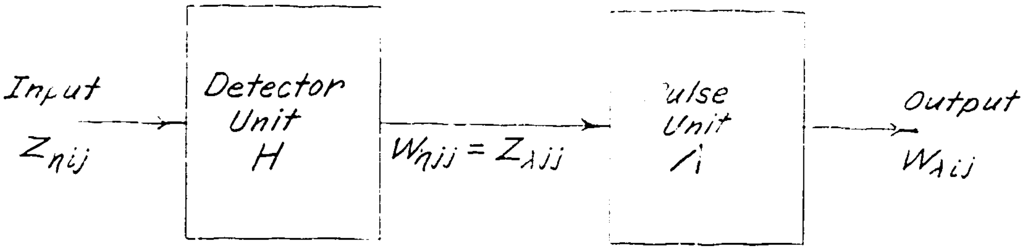
As described in the chapter on natural biological neurons and data obtained therefrom, the neuron or at least groups of neurons can act autonomously--that is, produce an output with no input being present. Whether this fact is actually a by-product of neuron existence or whether it is a necessity for neuron activity is not really agreed upon by various authorities. Therefore to provide an autonomous component which could be used if desired, but which need not be used at all in the Adaptive Reorganizing Automaton, a separate and distinct component was designed.

The ideal requirements for an autonomous component would require such a unit to produce pulses at random with respect to its environment but under certain restrictions just the same. At first this statement may seem contradictory but an example will clear it up. If the autonomous components were continuously in operation, then the neurons whose inputs were being excited by these autonomous components would consider them only as part of their environment which was always present and so would adapt to them, if only in the sense of learning to ignore their pulses which were completely random with respect to others. Therefore their purpose would be lost since one of the purposes of autonomous components is to activate the system when no external stimuli are present. Thus any autonomous components must be restricted in their randomness to operate only during periods of normal inactivity in the automaton.

Assuming this restriction then, the second requirement of an autonomous component was the randomness of pulse output during its limited operation. The best solution to this requirement would seem to be either a noise source or another complete self-organizing system to interact with the Adaptive Reorganizing Automaton.

Since neither of these solutions seemed economically practical, at least for the first model automaton, the next best solution was adopted. This is the acceptance of periodicity in the autonomous component provided this periodicity is extremely slow compared to the slowest "normal periodicity" of the automaton and also provided that this periodicity can be controlled by inputs so as to appear "partly random" from its output. With these requirements, the autonomous component shown in Figure 15 was designed.

The pulse unit is basically the same type as that used in the elementary component, except that it is autonomous in its unstimulated state. That is, the network constants are so chosen that, in the absence of any input pulses to the component, an internal control potential, E_c, increases exponentially with time at a very slow rate until it exceeds some threshold value, Θ_λ, at which time the pulse unit fires--i.e. it produces an output pulse. The production of the pulse reduces E_c to a very low value, E_o, from which it again



Some Typical Identities

$Z_{\chi ij} = W_{\nu ij}$ and/or $W_{\chi ij}$

$W_{\lambda ij} = Z_{\gamma^{+} ij}$ and/or $Z_{\epsilon ij}$

Figure 17. Autonomous Component Block Diagram

starts to increase exponentially. Thus the process is repeated and a periodic pulse output results, the repetition rate being about 10 pulses per second. This function may be written as:

$$W_{\lambda ij} = 0 \quad \text{when} \quad E_c \leq \Theta_\lambda$$

$$= 1 \quad \text{when} \quad E_c > \Theta_\lambda \text{ for a length of time } \delta t'' \tag{10}$$

where E_c varies between output pulses in the following manner:

$$E_c = E_o + (E - E_o)(1 - \epsilon^{\frac{t}{k}})$$

where:

$W_{\lambda ij}$ is the instantaneous output potential of the λ unit (always a standard pulse).

E_c is the instantaneous internal control potential of the λ unit.

Θ_λ is the threshold potential of the λ unit which determines the time of firing

$\delta t''$ is the minimum length of time required for the control potential to exceed Θ_λ to cause firing.

E is the supply potential of the internal control potential.

E_o is the value of E_c after firing.

k' is the time constant of the control potential circuit.

t is any time between output pulses as measured from the preceding pulse.

To prevent the continuous periodic firing of the λ unit, an input is provided which is connected directly to the control potential, E_c. Therefore, this potential can be reduced by pulsing the input with negative going pulses at the input and this is what the detector unit does.

The detector unit is basically a pulse inverter which accepts positive going pulses at the input and transmits negative going pulses at the output. Therefore its transfer function is simply:

$$W_{\eta jj} = -k_\eta Z_{\eta ij} \qquad (11)$$

where:

$W_{\eta ij}$ is the instantaneous output potential of the H unit (essentially a pulse).

k_η is a constant of the circuit.

$Z_{\eta ij}$ is the instantaneous input potential to the H unit (a pulse of varying amplitude).

Due to the previously mentioned input to the ∠ unit, if enough pulses of great enough amplitude are active at the component input within a given time interval, the internal control potential, E_c, can be kept below the threshold value, Θ_λ. indefinitely. However, when the pulses at the input are inactive for a length of time greater than the normal period of the autonomous component, the output unit will fire.

This can be seen from the general transfer function of the autonomous component, obtained by setting $W_{\eta jj} = Z_{\lambda jj}$, as indicated in Figure 15, and by the fact that the input pulses at the ∠ unit are integrated in the unit. Thus E_c can be expressed as:

$$E_c = \int_t k_\lambda Z_{\lambda jj} + \sum_t \text{(exponential terms)} \qquad (12)$$

where:

E_c is the instantaneous control potential with the input active.

k_λ is a constant of the circuit.

$\int_t$ is an integral taken over the period of time from the preceding output pulse.

$\sum_t$ means summing the exponential terms encountered sequentially in time.

The exponential terms are simply written between jumps in the E_c versus time curve as:

$$E_c = E_c' + (E - E_c')(1 - \epsilon^{-\frac{t-t}{k'}}) \qquad t' < t < t'' \tag{13}$$

where:

E_c' is the instantaneous control potential at time, t'.

t is any time such that $t' < t < t''$

$t'' - t'$ is the time interval over which the expression is true.

Then the transfer function for the autonomous component as obtained from Equations (10), (11), (12) and (13) is:

$$W_{\lambda ij} = 0 \quad \text{when} \quad E_c \leq \Theta_\lambda$$
$$= 1 \quad \text{when} \quad E_c > \Theta_\lambda$$

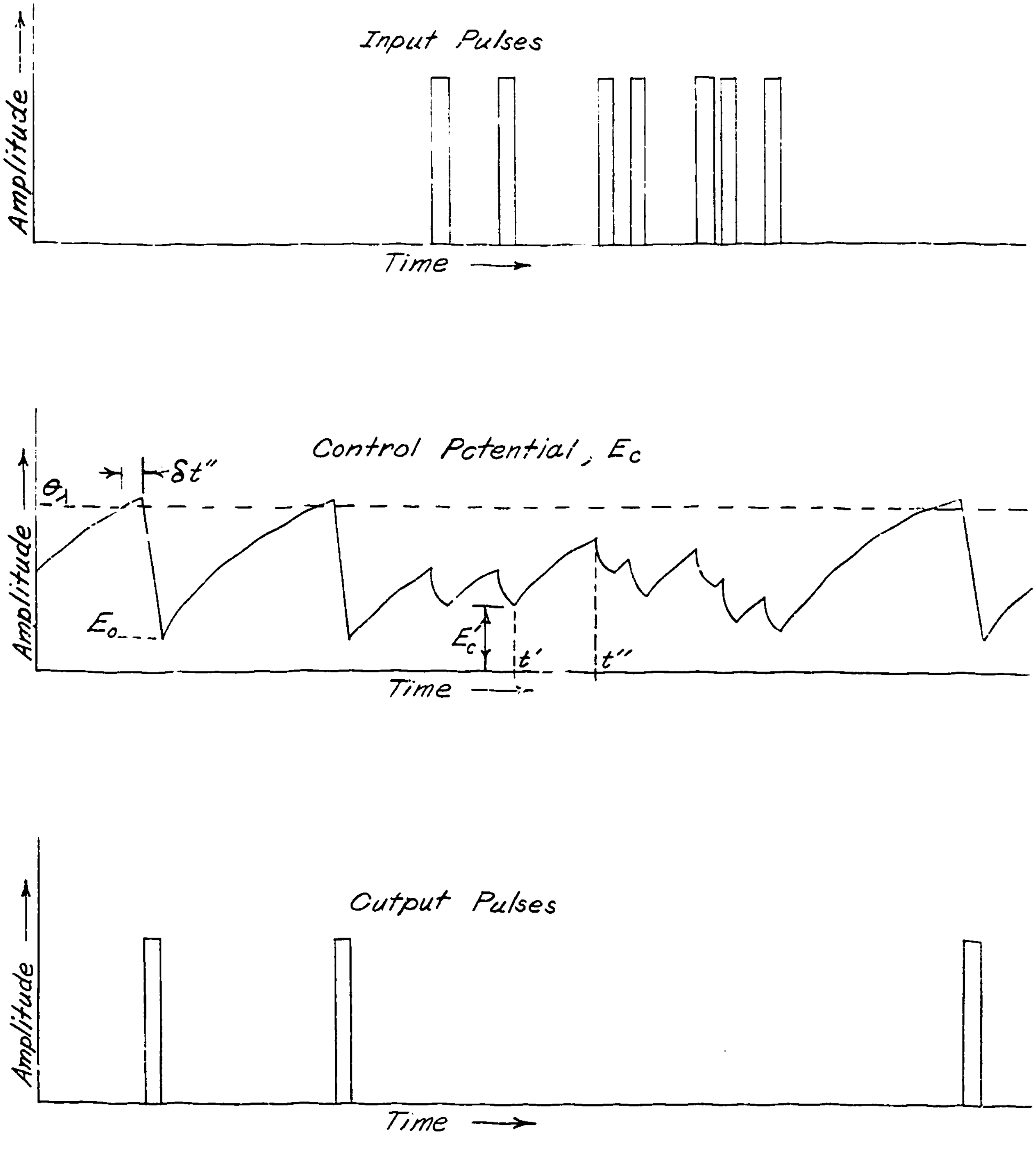
where:

$$E_c = -\int k_\lambda k_\eta Z_{\eta ij} dt + \sum_t [E_c' + (E - E_c')(1 - \epsilon^{-\frac{t-t}{k'}})]$$

when the last term is properly interpreted as indicated previously.

Reference to Figure 16 will illustrate the above functional variations as well as give the transfer function of the autonomous component.

The resulting autonomous component can be used at any position in the



(Not to scale)

Figure 16. Autonomous Component Function

computer to trigger an Energy Transducer and it can obtain input pulses from any or all of many different pulse sources, either by direct connection or through facilitators. Therefore, with respect to any one neuron which is triggered into firing by an autonomous component, the component will appear to be rather random in pulse repetition rate if the autonomous component inputs are properly chosen.

6. EXPERIMENTAL RESULTS

6.1 Automaton Physical Description

Before discussing some of the experimental results obtained thus far with the Adaptive Reorganizing Automaton, a short description of the physical components and their placement in the assembled units will be given. Also to be discussed is the relative complexity which is possible even with the very limited size of the present automaton.

The experimental realization of the various components described in Chapter 5 took the form of circuit modules, each module being constructed on a 2 inch by 3 inch phenolic terminal board. In certain instances each module contains only one functional unit such as the Energy Transducer shown in the two views of Figure 17. Shown here are the 12 input and one output wires which are connected to pin jacks through the front panel. Also apparent is the potentiometer used to control the manual threshold from the rear of the panel. Seven of these modules are mounted perpendicularly behind a standard rack panel which is 3 1/2 inches wide and 19 inches long. Four of these racks of Energy Transducers are available in the assembled automaton.

The modules shown in Figure 18 and Figure 19 are respectively the Autonomous Component module and the Facilitator module. Both these modules contain two functional units each. The simplicity of the Autonomous Component is quite apparent from Figure 18, whereas as shown in Figure 19, the Facilitator is somewhat more complex. Clearly shown in the Facilitator module are the two miniature 100 microfarad electrolytic capacitors used as storage elements and the two vacuum tubes used to isolate the storage elements. Fourteen Autonomous Component modules are mounted perpendicularly behind a standard 3 1/2 inch wide rack panel,

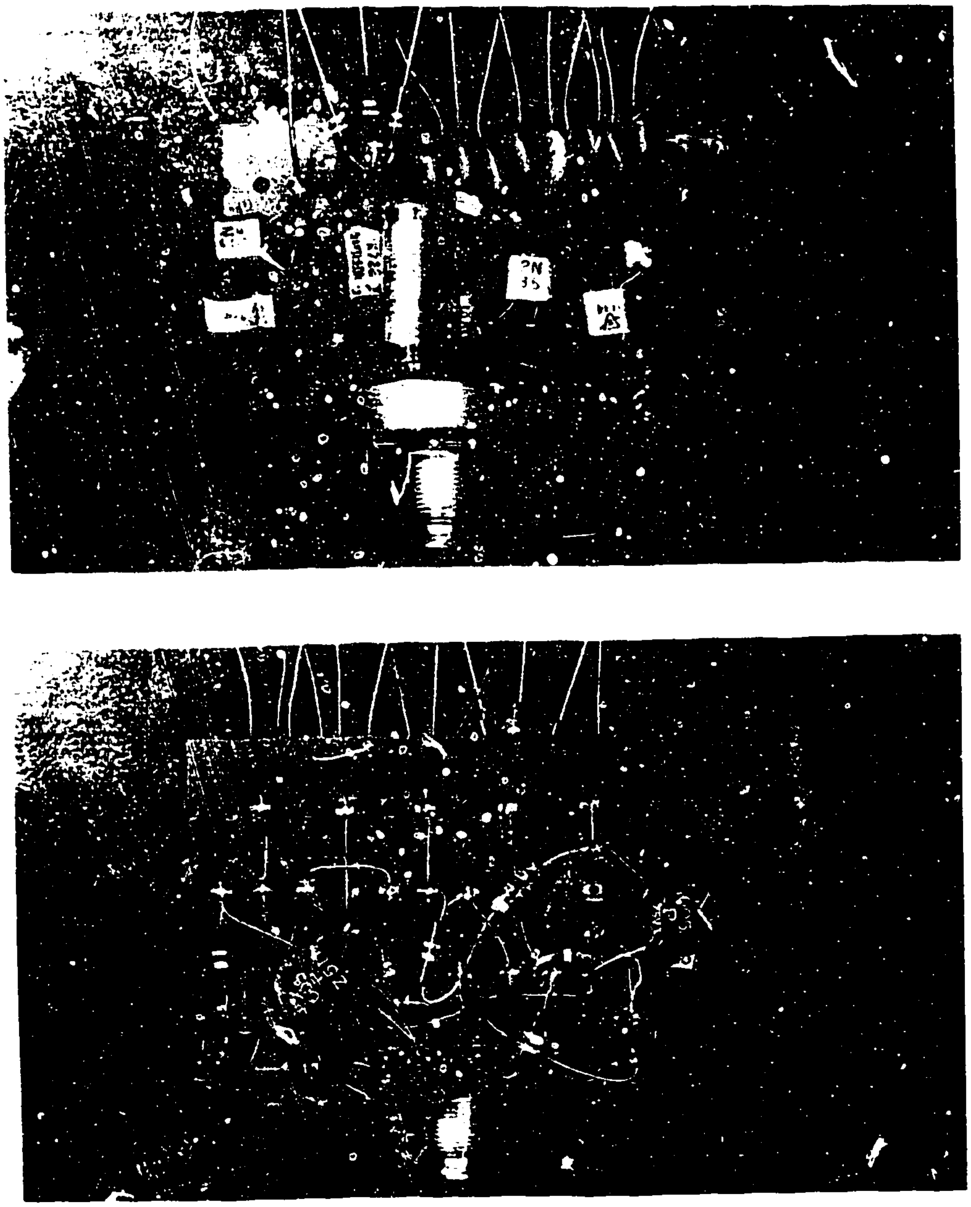


Figure 17. The Two Sides of the Energy Transducer Module

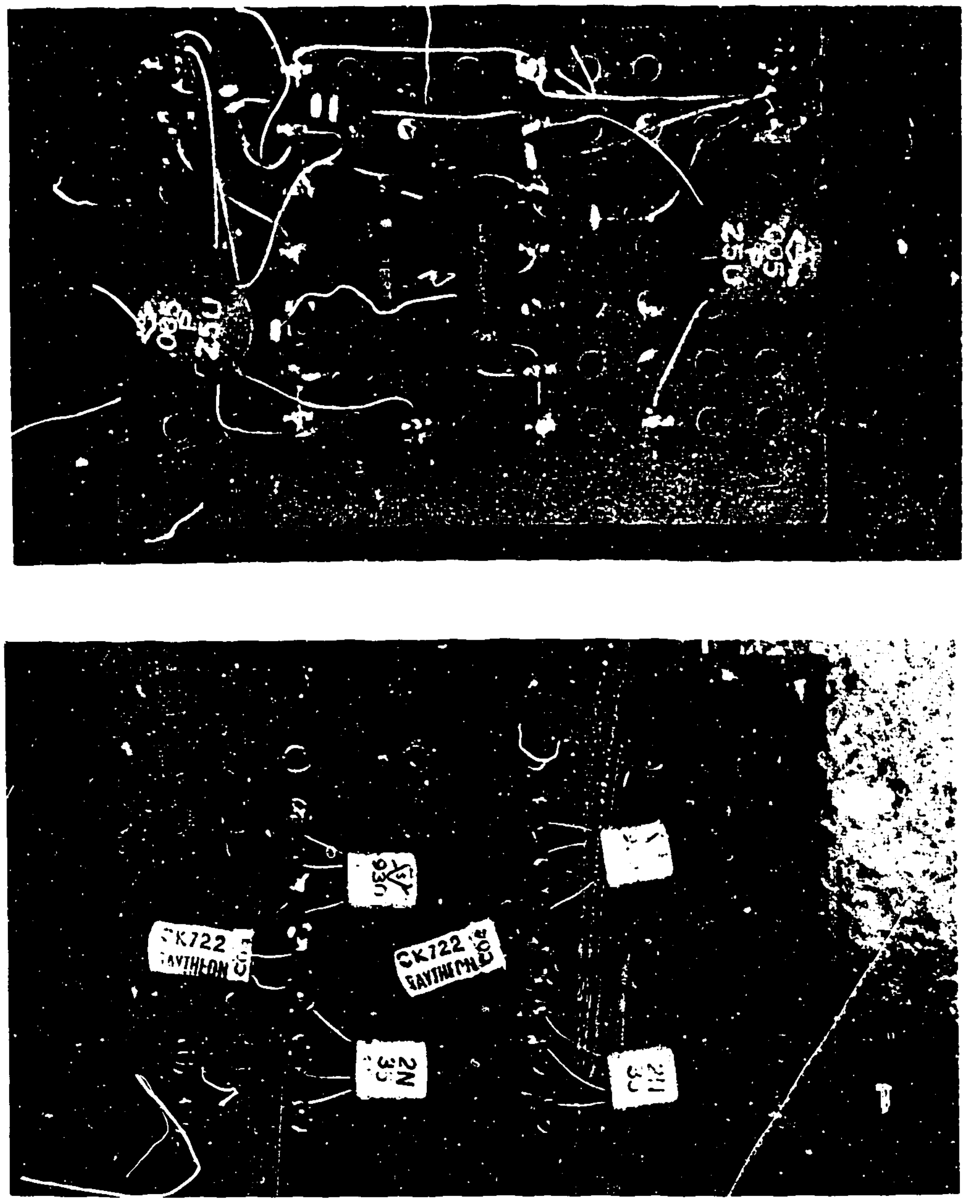


Figure 18. The Two Sides of the Autonomous Component Module

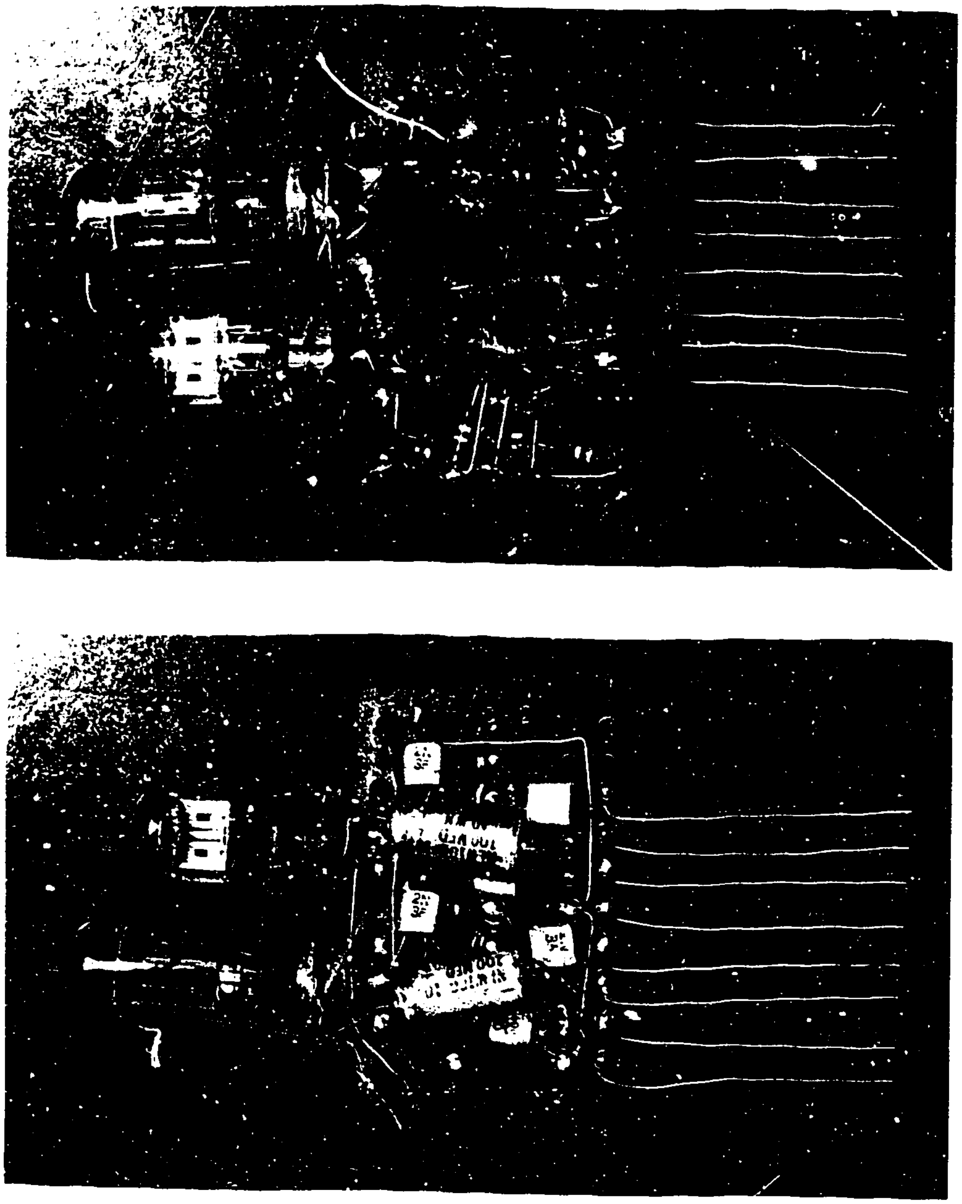


Figure 19. The Two Sides of the Facilitator Module

only one rack of this type being available in the automaton. There are four racks of Facilitators available in the automaton, each rack being 3 1/2 inches wide and containing fourteen Facilitator modules mounted perpendicularly behind it.

Thus the automaton contains a total of 28 Energy Transducers, 28 Autonomous Components, and 112 Facilitators. In addition it also contains 30 indicator tubes to be used as signal monitors and general operation pattern detectors. All operating connections between the various units of the automaton are made by means of pin jack connectors. These pin jacks are clearly visible in the photograph of the automaton shown in Figure 20. Connections between the various units may thus be made by means of wires, capacitors, resistors, diodes, or any impedance elements desirable, making the possible flexibility very great. Also the use of these connectors allows access to all the signal terminals for monitoring purposes.

Figure 21 is a photograph of the rear of the automaton. This view shows the placement of the various modules in the complete automaton. Referring to either Figure 20 or Figure 21, the identification of the various racks in the automaton are from top to bottom: 2 Energy Transducer racks, the rack of indicator tubes, a Facilitator rack, an Energy Transducer rack, a Facilitator rack, the Autonomous Component rack, a Facilitator rack, an Energy Transducer rack, and a Facilitator rack.

6.2 Component Experimental Results

The functioning of the individual components will now be illustrated with the aid of experimental data. For example, Figure 22 is a photograph of three pairs of oscilloscope traces of the excitatory input and the resulting output pulses of an Energy Transducer. The top pair of traces shows an input

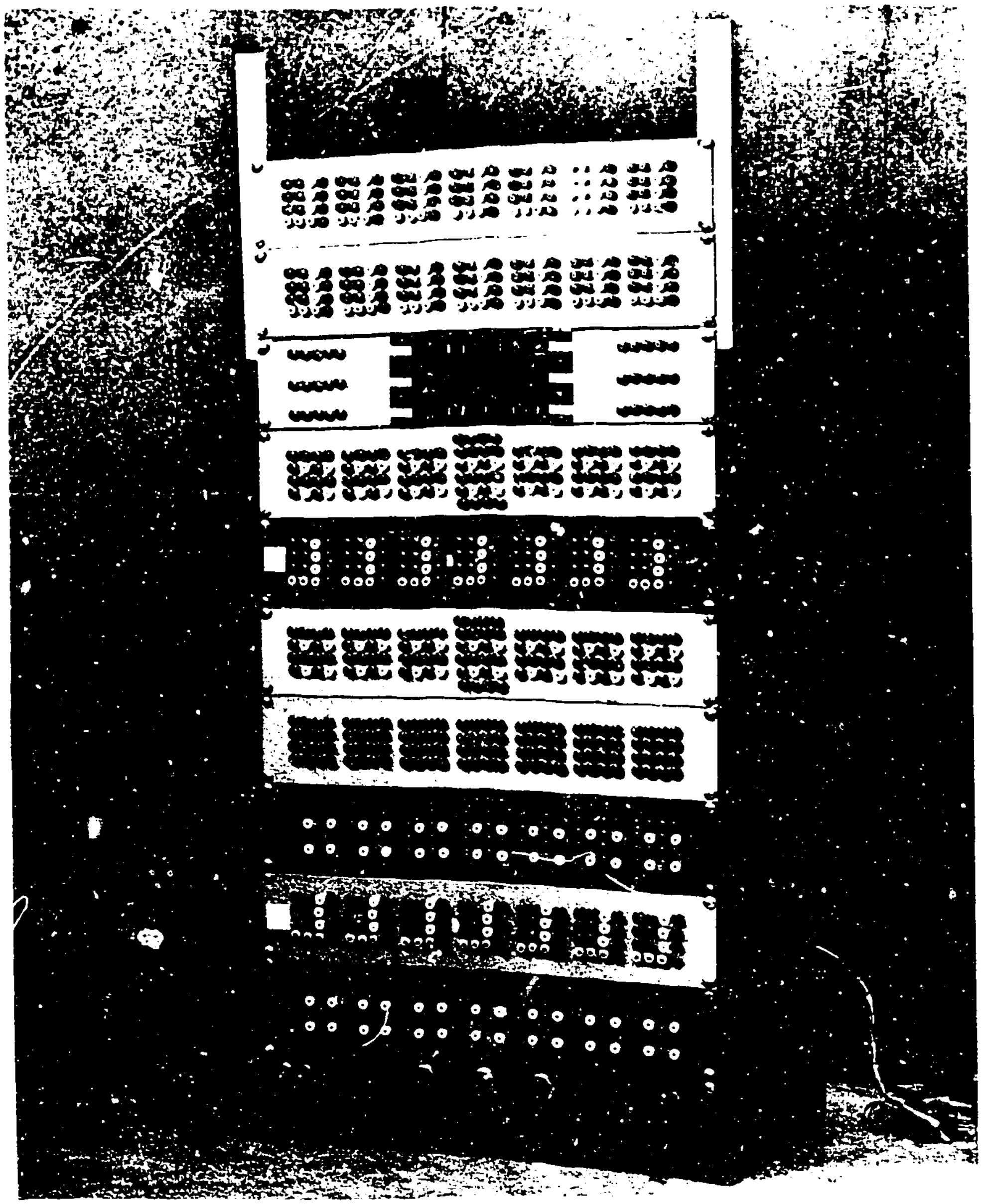


Figure 20. Front View of Adaptive Reorganizing Automaton

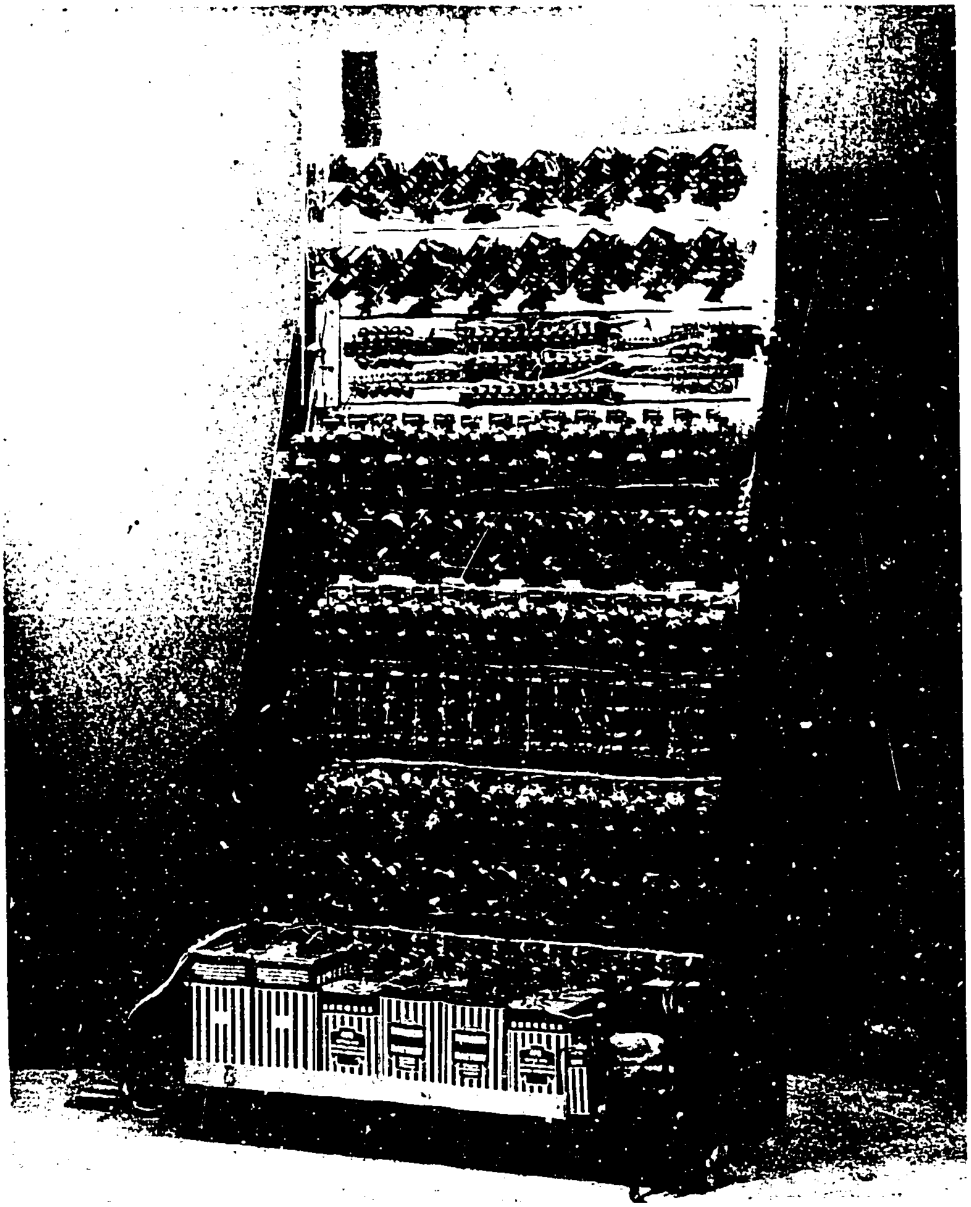
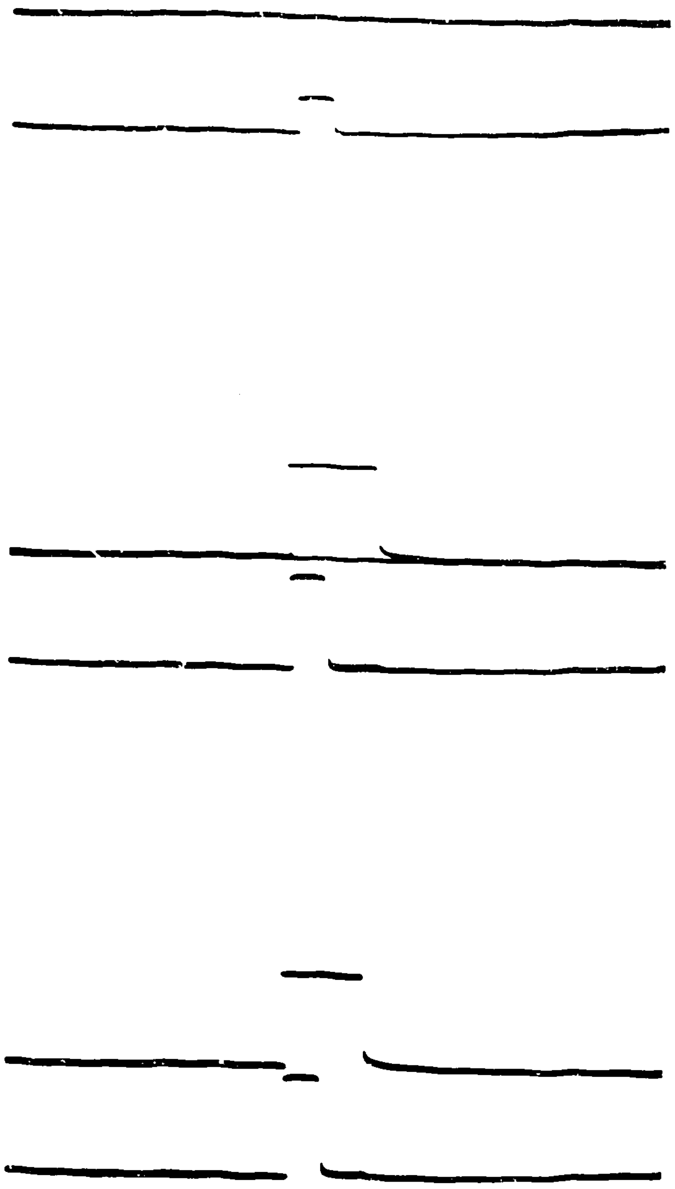


Figure 21. Rear View of Adaptive Reorganizing Automaton



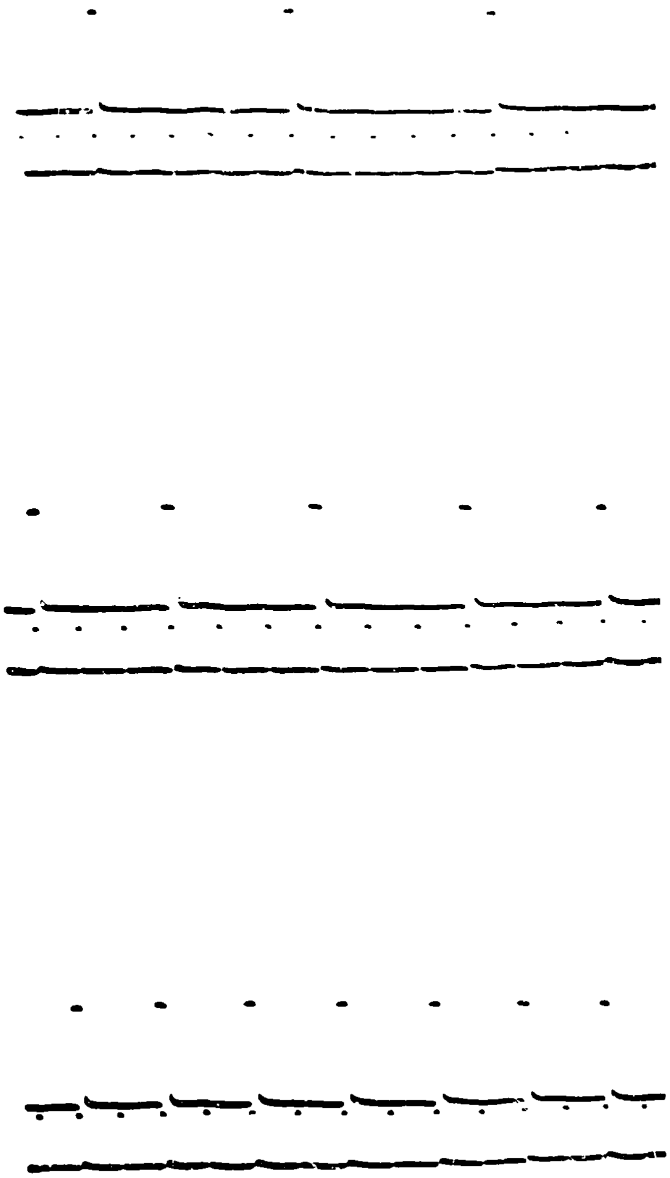
Note: Bottom trace of each pair is the imput trace.

Figure 22. Effects of Various Amplitude Excitatory Input Pulses upon an Energy Transducer with Fixed Threshold Level.

pulse whose amplitude is insufficient to cause an output pulse. The middle pair of traces shows an input pulse on the bottom of the pair of traces and an occasional output pulse on the top trace of the pair. The fact that only an occasional pulse is present is shown by the presence of a base line across the entire output pulse. The reason for the occasional pulse output is the refractory time of recovery after an output pulse. This is explained more fully later with respect to Figure 23. In the bottom pair of traces of Figure 22, the amplitude of the input pulse shown on the bottom trace is sufficient to cause an output pulse at all times.

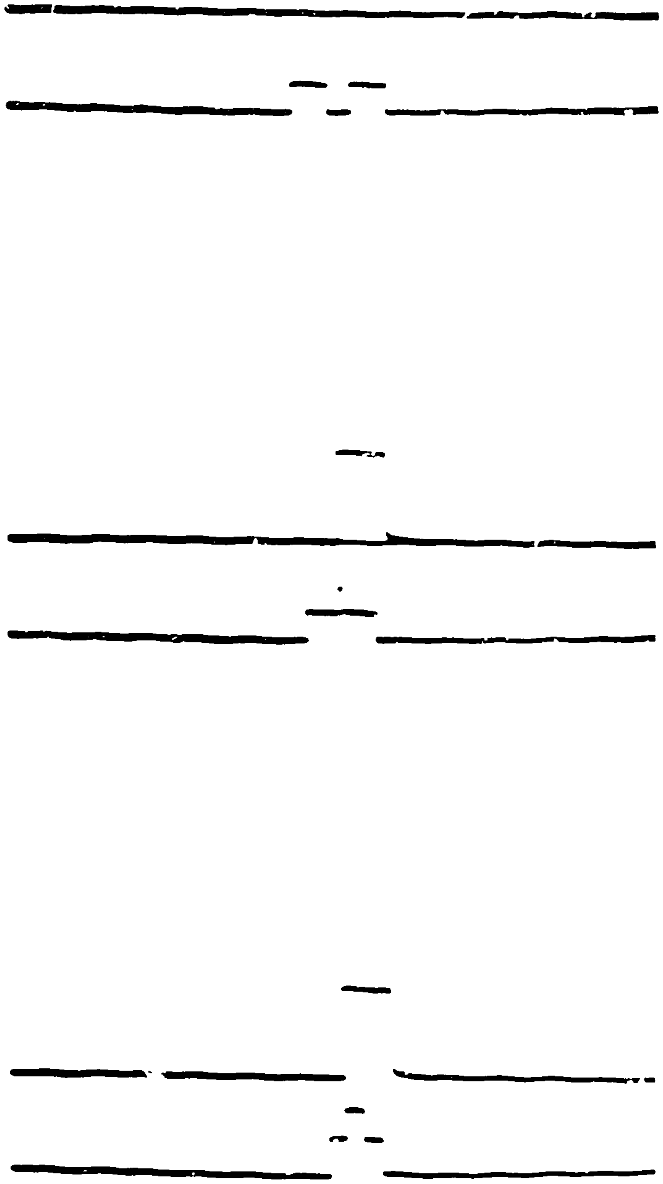
Figure 23 presents some of the same data as Figure 22 but with the time axis compressed considerably. From this figure it is apparent how the output pulse repetition rate is a fraction of the input pulse repetition rate. This effect is caused by a combination of the input pulse amplitude with respect to the threshold value of the Energy Transducer and the input pulse repetition rate. This can be explained as follows. Following an output pulse from an Energy Transducer, the threshold value returns to its quiescent value exponentially with time. Therefore, the amplitude and repetition rate of the input excitatory pulses will determine the time when the decreasing threshold value is just exceeded by an input pulse of sufficient amplitude to trigger the Energy Transducer output pulse. Thus the effect is a division of the input pulse repetition rate. Figure 23 presents the effect clearly in three pairs of oscilloscope traces, the input pulses shown on the bottom trace of each respective pair. The change in input pulse amplitude over the three pairs of traces is very evident.

Figure 24 illustrates the summation of two excitatory pulses active at the input of an Energy Transducer. The top pair of traces shows two pulses active



Note: Bottom trace of each pair is the input trace.

Figure 23. Frequency Division of Input Pulse Repetition Rate Due to Different Input Pulse Amplitudes.



Note: Bottom trace of each pair is the input trace.

Figure 24. Summation of Excitatory Input Pulses To Produce an Output Pulse from Energy Transducer.

at the input, but separated in time such that no output results since each pulse amplitude is below the threshold value of the Energy Transducer. The second pair of traces shows the summation of two pulses such that an output pulse results occasionally when the two pulses are added. This effect is the same as that described previously in Figure 23. The bottom pair of traces shows an output pulse for each summation of input pulses. In this instance the time between the arrival of the two pulses is sufficiently small so that in every instance the pulse summation energy is great enough to produce an output pulse every time instead of just occasionally.

This time of summation seems reasonably important. For example, assume a pulse signal traverses the paths shown in Figure 25.

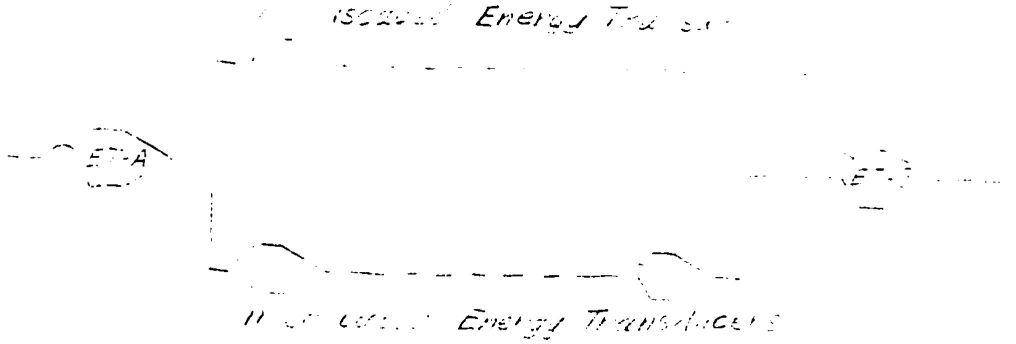


Figure 25. Control of Energy Transducer B by Means of Parallel Signal Paths of Different Lengths.

The output of ET-A (Energy Transducer A) excites two separate paths which evemtually are united at the input to ET-B. Here the input pulse amplitude and the ET-B threshold are such that neither pulse by itself will trigger ET-B output. The delay of a pulse in transit through an Energy Transducer is variable, being a function of the input pulse amplitude relative to the threshold, but in general it is from one to four microseconds Thus the summation time of input pulses to ET-B determines the difference in the numbers n and m of Energy Transducers which can be traversed by a pulse and still cause ET-B to produce an output pulse. The present times are such that this difference can be from 10 to 20.

There are two more features of the Energy Transducers which can be experimentally shown. These are the autonomous nature of the transducers and the change in threshold due to pulses active at the pulse threshold input. The former is shown in Figure 26. The threshold of the (+) Energy Transducer was set to 4.0 volts--i.e. a pulse of 4.0 volts amplitude was required to trigger the output of the Energy Transducer--and then the pulse threshold input was excited by standard pulses of varying repetition rate. As shown, the result was output pulses of varying repetition rate, the output pulses being generally uncorrelated with the input pulses. However, there is generally a gain in the repetition rate of the output pulses compared to the repetition rate of the input pulses, this gain varying from six at an input of 50 pps. to about three at an input of 500 pps. Thus it is possible to get a form of pulse repetition rate increase by this method of excitation.

Figure 27 shows the change of threshold value of both a (+) and a (-) Energy Transducer due to pulse threshold input activity. It will be seen that the threshold value for a (+) Energy Transducer decreases from 8.4 volts to 4.8 volts for a pulse input change from 0 to 500 pulses per second repetition rate, whereas the threshold value for a (-) Energy Transducer increases over about the same values for the same change of input pulse repetition rate. Thus effects similar to both positive and negative feedback are possible with these two types of Energy Transducers.

For the experimental confirmation of the functioning of the Facilitator, refer to Figures 28 and 29. Figure 28 shows the gain of the Facilitator as a function of the length of time of activity of the (+) facilitation input and of

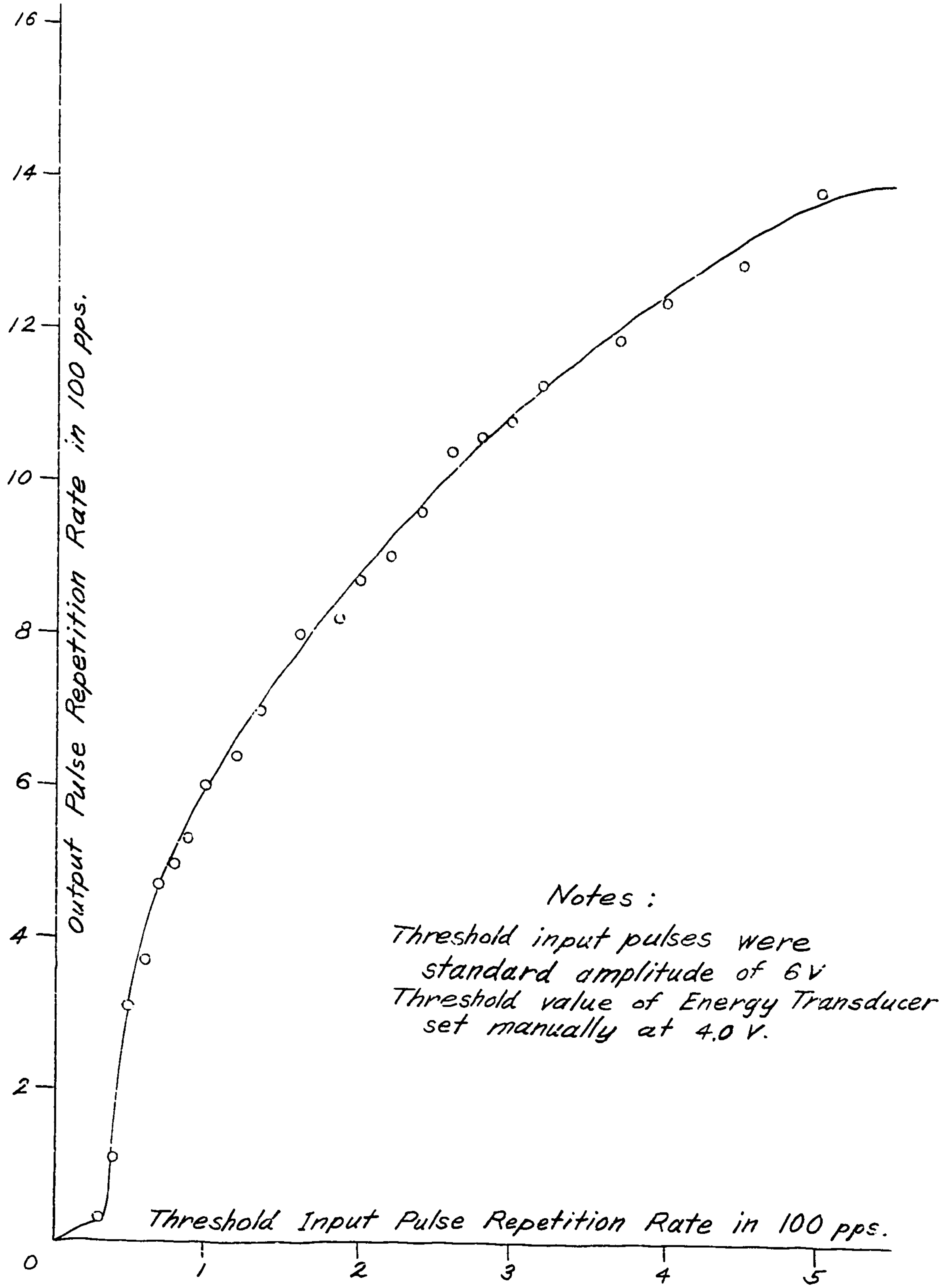


Figure 26. Autonomous Output of (+) Energy Transducer When Only Pulse Threshold Input Is Active

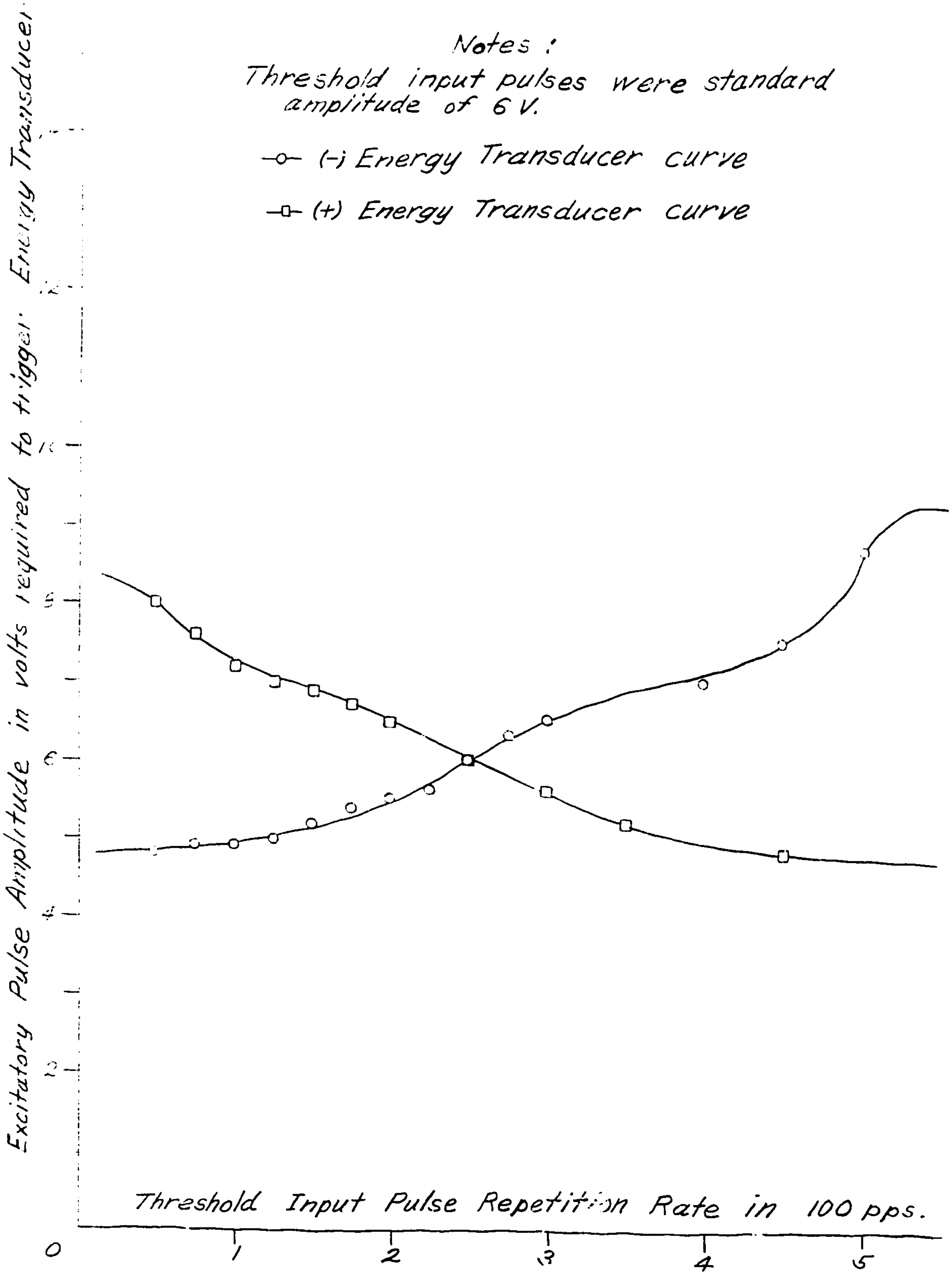


Figure 27. Threshold Variation of Energy Transducers

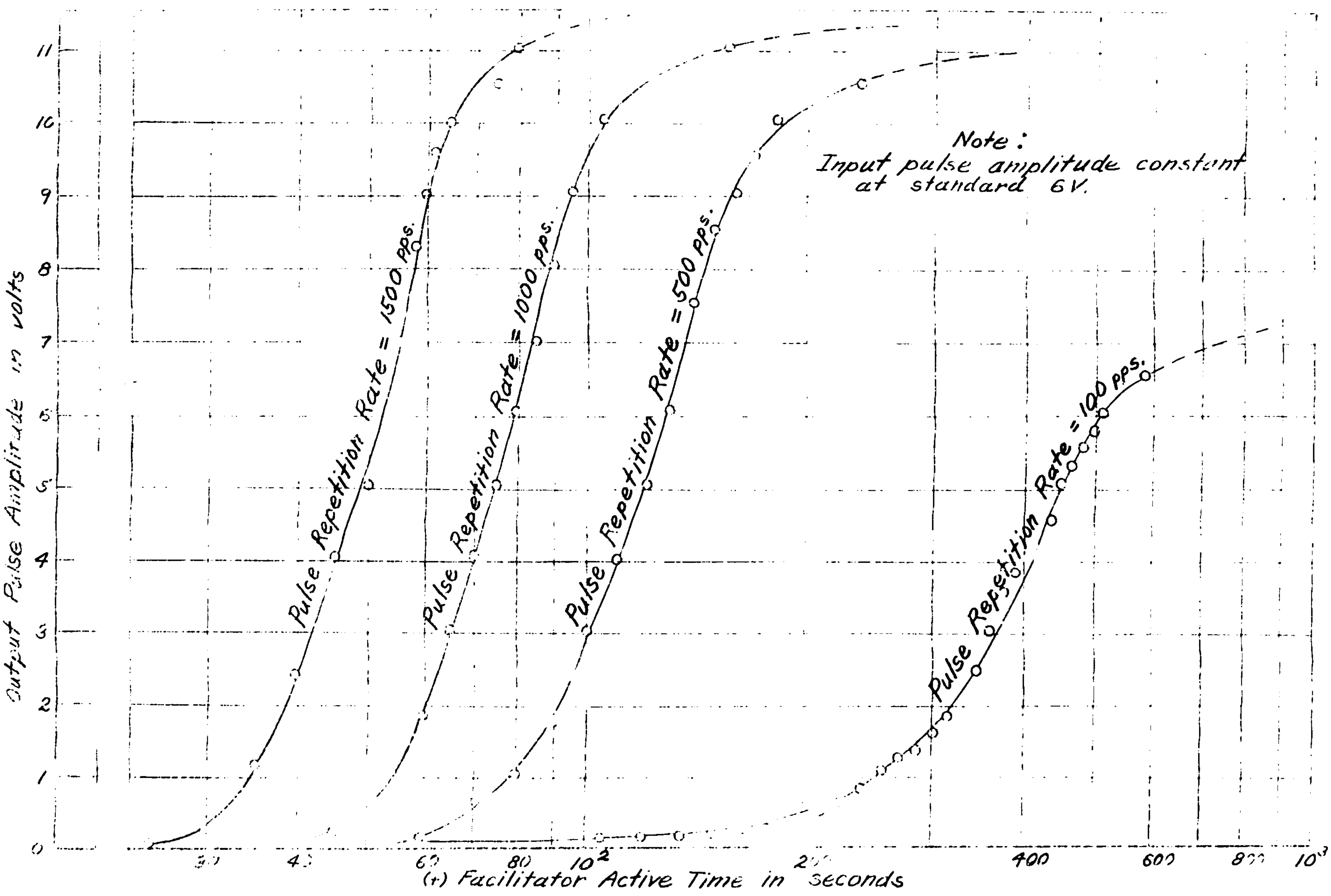


Figure 28. Facilitator Gain as a Function of Input Active Time and Input Pulse Repetition Rate

the input pulse repetition rate. That is, starting the Facilitator at zero gain and continuously exciting the (+) facilitation input with a fixed pulse repetition rate and standard amplitude (6 volts), the gain will vary in the manner shown. For example, at an input of 500 pps., the gain does not become noticeably different from zero until about 60 seconds of activity, after which it rises rather rapidly to its saturation value in about 300 seconds. It will be noticed that the curves all have the same general shape, being only shifted horizontally to the right from each other and decreasing in saturation value as the input pulse repetition rate decreases. The saturation value is dependent upon an equilibrium between the input pulse energy and the leakage energy between pulses from the storage element, and so as the input repetition rate decreases, the saturation gain value decreases.

With reference to the Facilitator gain decay, Figure 29 shows a characteristic decay for two different manners of saturation. The top curve was obtained by first manually saturating the Facilitator and then allowing it to decay with no further excitation except an occasional test signal pulse. The bottom curve was similarly obtained except that initially the saturation was obtained by pulse excitation. It is seen that both curves are essentially the same except for amplitudes.

6.3 System Experimental Results

Before considering some of the simple results obtained thus far with the present automaton, a little explanation about the possible complexities is in order. From considerations of the various experimental results of the Energy Transducer and the Facilitator given in the last section, it is apparent that each of these components is very flexible and may have various functions in a circuit. For example, the Energy Transducer can serve as a logical "or"

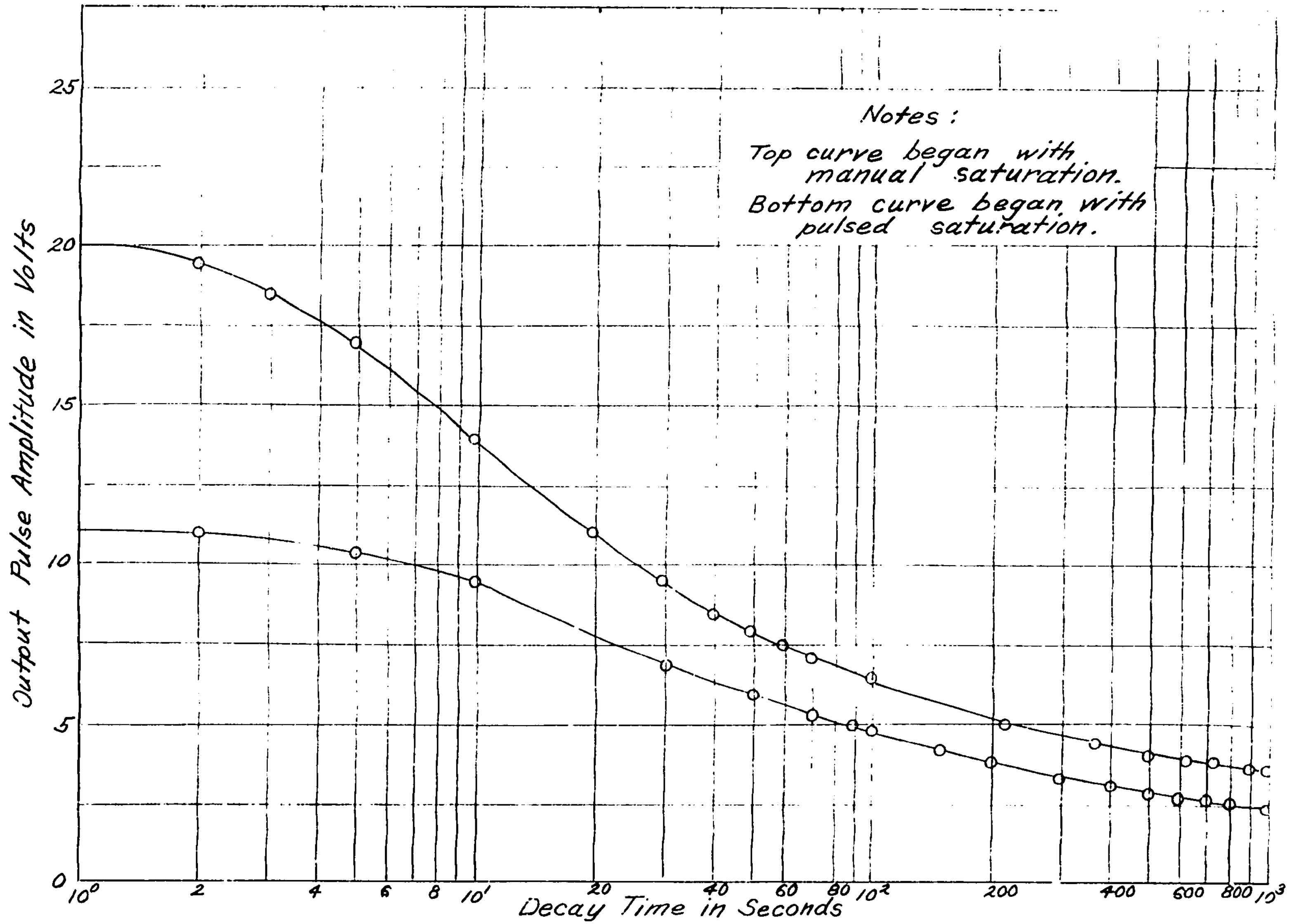


Figure 29. Facilitator Gain Decay as a Function of Time.

circuit, a logical "and" circuit, a "summing" circuit, a pulse repetition rate divider, a pulse repetition rate multiplier, etc., when the parameters--particularly the thresholds--are properly established. When this unit is combined with the adaptive unit of the system, the Facilitator, then a truly complex and flexible component is possible.

Considering only these components, it is readily apparent that tremendous interconnectivity is possible. Figure 30 shows how one Energy Transducer, one Autonomous Component, and nine Facilitators are connected to form a combination element which has some of the information digestive capabilities of a biological neuron. As shown, there are three E inputs (Excitatory), three I inputs (Inhibitory), three T inputs (Threshold), three C inputs (Continuous Threshold), and one output on each Energy Transducer. Each Facilitator has one (+) facilitation input, one (-) facilitation input, and one output. Thus Figure 30 is an Elementary Component which has a total of 21 inputs and one output. If components as shown are considered and only the 18 pulse inputs are used, then there are

$$\sum_{t=0}^{n} \binom{18}{t} = \left(2^{18}\right)n^{2} = 2^{18n^{2}}$$

possible systems for n Elementary Components. This is a very large number of systems for only a small number of components as shown in Table II. It is true that within these possible systems there are many functionally redundant connections and also many connections which do not make a totally connected system, but even considering these possibilities, it is seen that the total number of systems which can be studied with even this limited automaton--the Adaptive Reorganizing Automaton--is extremely large. Thus it is fairly obvious that no exhaustive treatment of all the systems is possible nor is it the purpose

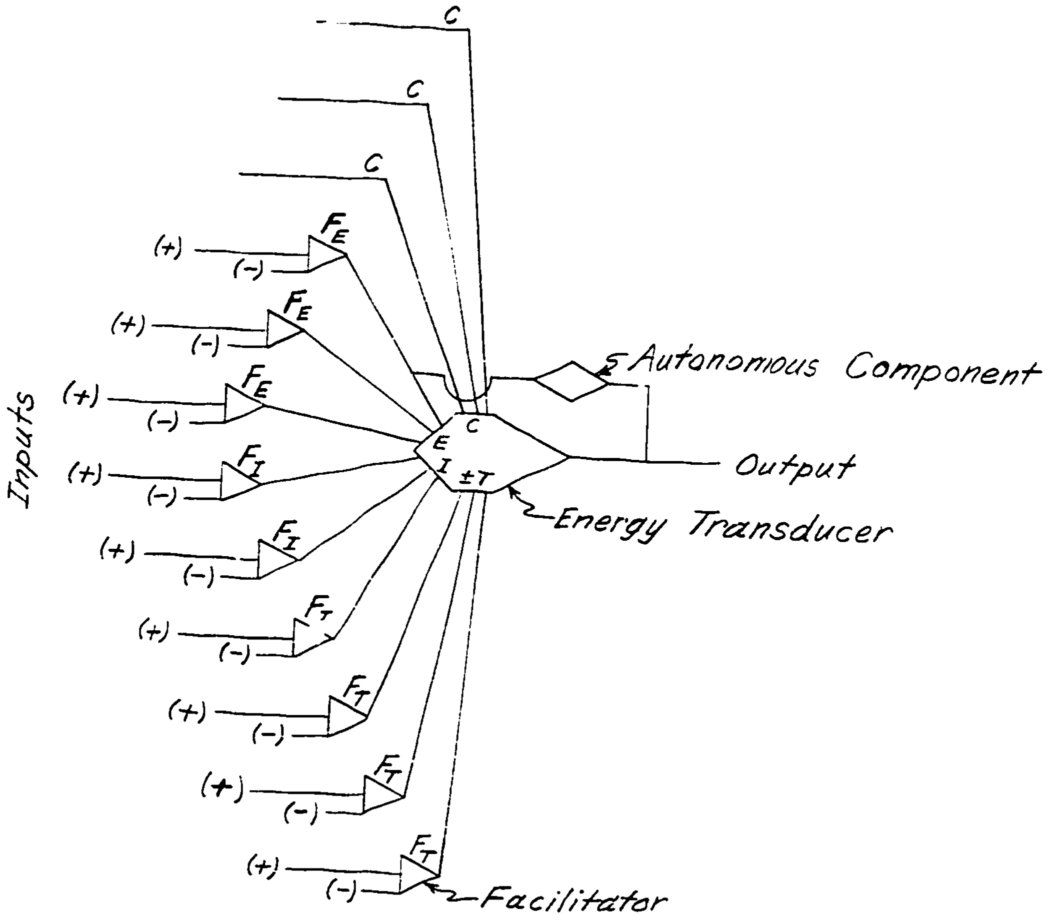


Figure 30. General Elementary Component

TABLE II

Number of possible systems containing n or less Elementary Components

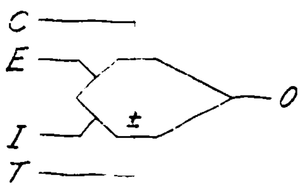
No. of Elementary Components	No. of Possible Systems		
	$\sum_{t=0}^{n} \overset{18}{t}$	$= 2^{18n^2}$	
1	2^{18}	$= 10^{5.42}$	$= 2.62(10^{5})$
2	$2^{18(4)}$	$= 10^{21.7}$	$= 4.70(10^{21})$
3	$2^{18(9)}$	$\doteq 10^{48.8}$	$= 5.78(10^{48})$
4	$2^{18(16)}$	$= 10^{86.7}$	$\doteq 4.88(10^{86})$
5	$2^{18(25)}$	$\doteq 10^{135.5}$	$= 2.82(10^{135})$
....			
10	$2^{18(100)}$	$= 10^{541.8}$	$= 6.31(10^{541})$
....			
12	$2^{18(144)}$	$= 10^{780.2}$	$= 1.56(10^{780})$

here to present such a study. It is only the purpose of this section to illustrate some systems using some of the components described and which have varied functions and adaptivity depending upon the manner of interconnection.

Table III illustrates some of the various possible sub-systems. The table is self-explanatory, each circuit containing a note of explanation beside it. Checking through the table, it is seen that various functional systems are possible, such as repetition rate filters, amplitude filters, repetition rate dividers, coincidence circuits, order detectors, counters, and others. Some of these are adaptive, being both time and previous history dependent. It is seen that most of the circuits are easily analysed functionally, but at the same time it is apparent that when the circuit interconnections become great enough and the environment complex enough, then the circuits can only be analyzed and predicitively studied by means of this or a similar automaton.

TABLE III

SOME REPRESENTATIVE POTENTIAL CONNECTIVITY CIRCUITS. (The explanation of the circuit function is shown at the right of each individual circuit)



Symbol for Energy Transducer (ET).

C is Continuous threshold input (3 possible).

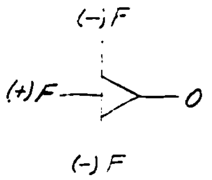
E is Excitatory input (3 possible).

I is Inhibitory input (3 possible).

T is Pulse Threshold input (3 possible).

O is output.

± in symbol indicates (+) or (-) Energy Transducer respectively.

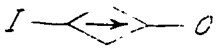


Symbol for Facilitator (F).

(+) F is positive facilitation input.

(-) F is negative facilitation input.

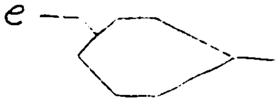
O is output.



Symbol for Autonomous Component (AC).

I is input.

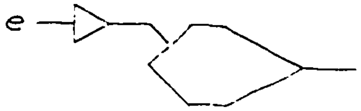
O is output.



Circuit 1

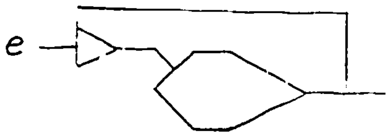
Non-adaptive element which is a pulse amplitude filter. With more inputs, it will serve as a pulse adder with respect to time and within limits with respect to amplitude.

e is an environment which is always a pulse source of some type.



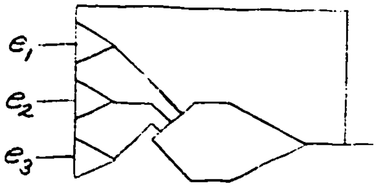
Circuit 2

Same as Circuit 1 with F added making the circuit adaptive in the sense that e does not trigger ET until e has been active for some time and will only continue to trigger ET if e is not off longer than the time required for F to decay below a certain value.



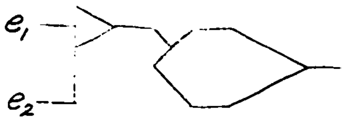
Circuit 3

Same as Circuit 2 with (-) F connection added. This makes output rep. rate less than e, the ratio depending upon the relative influence of the (+) F and (-) F inputs upon the gain of the facilitator. Also decreases adaptive influence of F since it cannot have a gain much greater than that required to trigger ET.



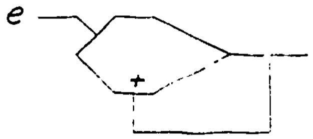
Circuit 4

This circuit adapts to the environment having the greatest average rep. rate--the e with the greatest average rep. rate. It will adapt to a different e if the former e becomes inoperative for a long enough period of time. Thus e's which are inactive for periods of time become un-influential.



Circuit 5

If rep. rate of e_1 is considerably greater than that of e_2 for an adaptive time then ET will be triggered by e_1, otherwise ET does not produce an output. Thus this circuit is a relative rep. rate detector.

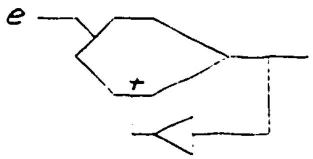


Circuit 6

This circuit becomes autonomous if rep. rate of e is great enough for a time dependent upon threshold setting and threshold integration time.

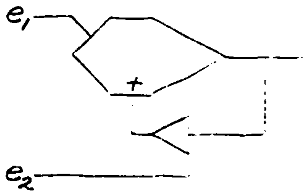
Once it is autonomous the rep. rate of the output increases very slowly over several minutes until it saturates at about 200 pps.

If the circuit does not become autonomous, then it shows hysteresis with respect to input pulse amplitude.



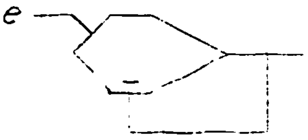
Circuit 7

Same as Circuit 6 with F added. This effectively increases the time required to drive the circuit to autonomy and also increases the saturation rep. rate.



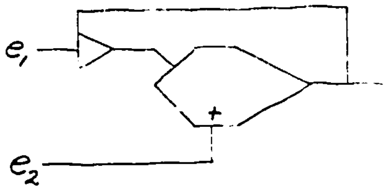
Circuit 8

Same as Circuit 7 with (-) F input added. This makes it possible to drive the circuit out of autonomy if e_2 is active long enough and with a high enough rep. rate. These are both dependent upon the length of time the circuit has been autonomous.



Circuit 9

Same as Circuit 6 but using a (-) ET instead of a (+) ET. The result is that the output rep. rate is less than that of the input rep. rate, the ratio being a function of the input freq., decreasing as the input rep. rate increases. This circuit is a form of frequency compressor.

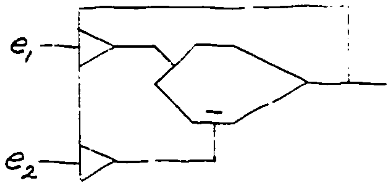


Circuit 10

This circuit responds to changes in rep. rate of e_2 in the following manner:

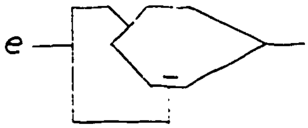
$de_2/dt > 0$ causes the output rep. rate to increase temporarily, after a period of time returning to its former output rep. rate.

$de_2/dt < 0$ causes output to cease, after a period of time returning to its former output rep. rate.



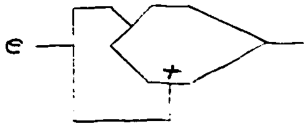
Circuit 11

Same as Circuit 10 but with (-) ET instead of (+) ET. The result is that the changes in output rep. rate are exactly opposite to those of Circuit 10.



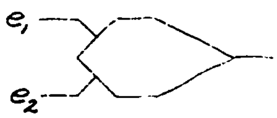
Circuit 12

Circuit responds to certain input rep. rates below a given value dependent upon the threshold setting. It is essentially a low pass filter.



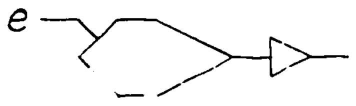
Circuit 13

Same as Circuit 12 but with (+) ET instead of (-) ET. Response is exactly the opposite of Circuit 12. It is essentially a high pass filter.



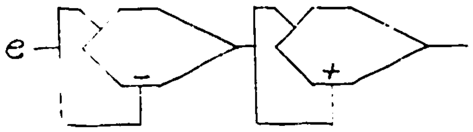
Circuit 14

Circuit does not produce a pulse out when pulses of e_2 are coincident with those of e_1 over a range of time, this time being dependent upon the threshold setting and pulse amplitude.



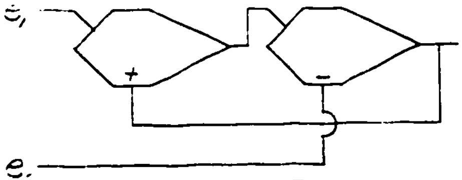
Circuit 15

Amplitude of output pulses increase as the ET is active over a period of time. This circuit is basically a form of neuron proposed by Eccles.



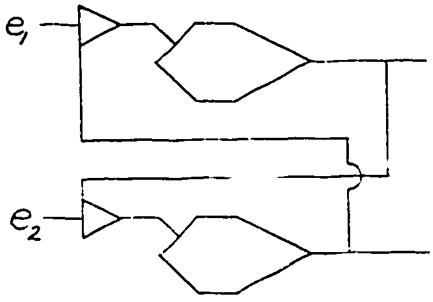
Circuit 16

Circuit is a band pass filter for certain settings of the ET thresholds.



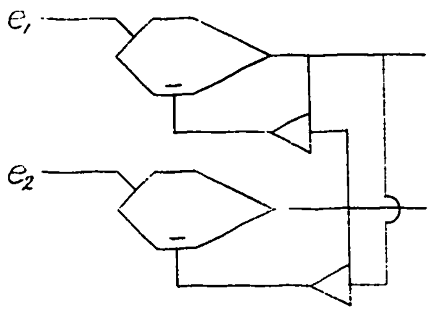
Circuit 17

Similar function as Circuit 8 but can be driven out of autonomy more easily than can circuit 8.



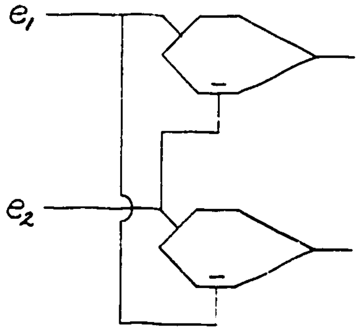
Circuit 18

Selects which output shall be active at corresponding e rep rate and excludes other output if its corresponding e rep. rate is less than the first e rep. rate. Will interchange this function after an adaptive period of the opposite environment condition.



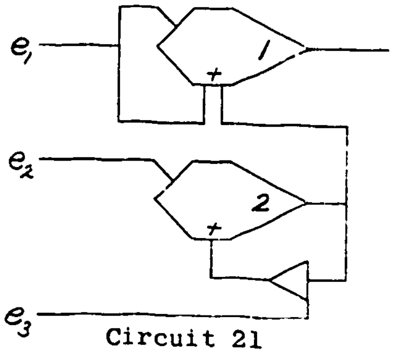
Circuit 19

This circuit shows very adaptive characteristics. If both e_1 and e_2 are equally active then both outputs are active. After an adaptive period of e_1 predominantly active, the circuit responds predominantly to the order of application of environments e_1 then e_2. However, it will respond to the other order of application momentarily. It can also be readapted to the opposite condition. This is a form of order detector.



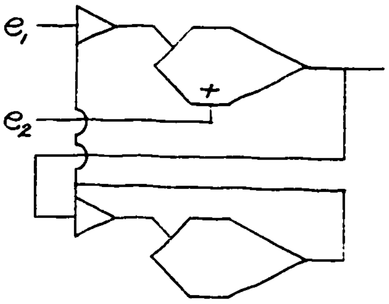
Circuit 20

This circuit is an order of excitation detector. If e_1 and e_2 are simultaneously active with the same average rep. rate then both ET's have an output momentarily, the time being dependent upon the integration time of the (-) ET. If either e_1 or e_2 is activated first for an appreciable time before the other then only that corresponding ET is activated momentarily.



Circuit 21

This is a combination of Circuit 13 and Circuit 8. Normally ET-1 is a high pass filter. When ET-2 is triggered to autonomy by e_2 then the low frequency cutoff value of ET-1 increases slowly. It returns to normal when ET-2 is driven out of autonomy by e_3.

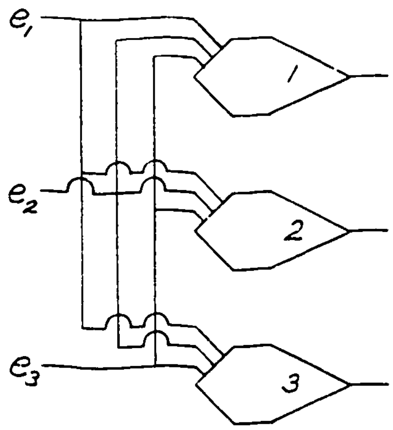


Circuit 22

This circuit responds to slow changes in rates of e_2 as follows:

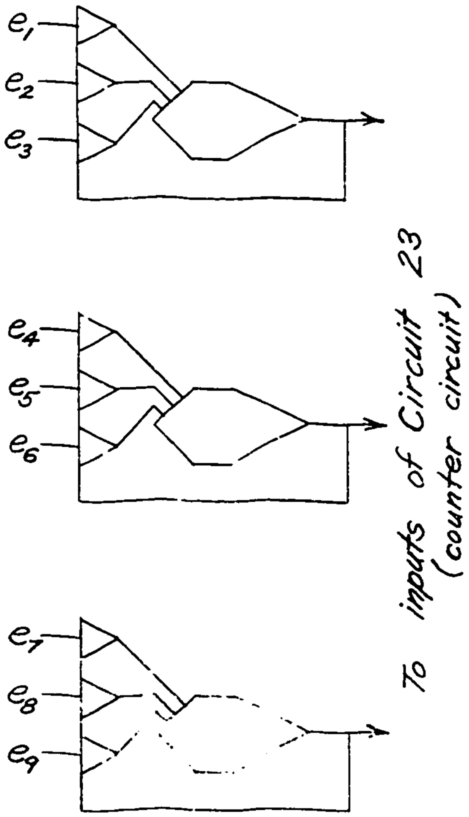
$de/dt > 0$ then output rep. rate increases

$de/dt < 0$ then output rep. rate decreases or momentarily stops.



Circuit 23

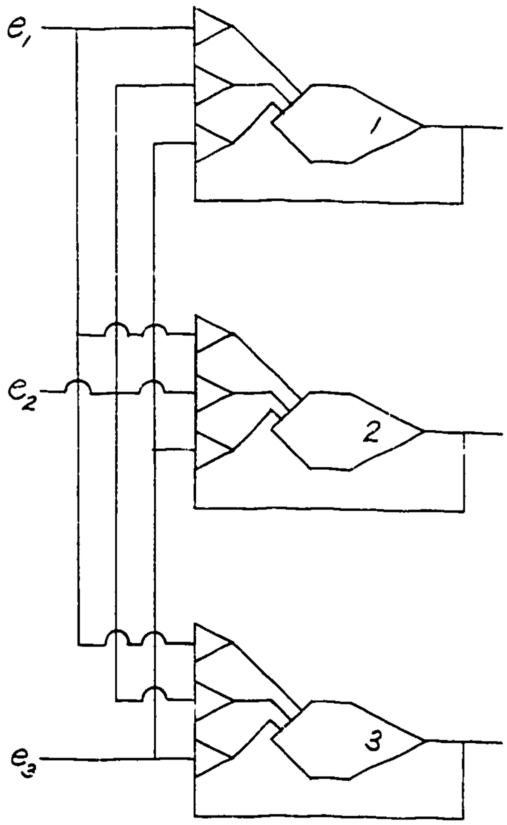
The ET thresholds are set so that three simultaneous pulses are required to trigger ET-3, two simultaneous pulses are required to trigger ET-2, and one pulse is required to trigger ET-1. Under these conditions the circuit becomes a simultaneous pulse counter any e activating ET-1, any two e's producing simultaneous pulses activating ET-1 and ET-2 and all three e's producing simultaneous pulses activating ET-1, ET-2, and ET-3. When the e's are always simultaneous pulses, but not all active then the circuit becomes simply a counter.



Circuit 24

This circuit functions as an input distribution pattern detector. For example, assume e_2 average rep. rate considerably greater than e_1 or e_3. Similarly for e_4 with respect to e_5 and e_6, and also the same for e_9 with respect to e_7 and e_8. Under these conditions and with the circuit attached to Circuit 23 as indicated, the entire circuit responds to these particular environment e coincidences but not others. That is, for example, e_2 and e_4 producing pulses coincidentally will cause the counter indication to be 2--i.e. ET-1 and ET-2 of Circuit 23 to be triggered. Similar pulses are produced for e_2 and e_9 coincidences and for e_4 and e_9 coincidences. However, other environment coincidences of pulses do not affect the output similarly.

This circuit can be readapted to a different input coincidence pattern by changing the ratios of the rep. rates of the input environmental e's.

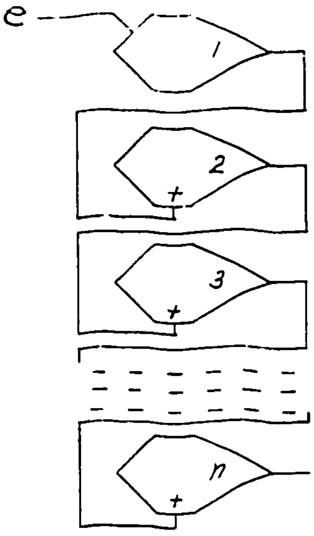


Circuit 25

This is a trainable adaptive circuit. For example, set the thresholds as in Circuit 2? then perform the following experiment: Use the same pulse source for all the e's; that is, all the e's when active are in synchronism. Apply e_1 until ET-1 triggers. Apply e_1 and e_2 simultaneously until ET-2 triggers also. Apply e_1, e_2, and e_3 simultaneously until ET-3, in addition to the other ET s, triggers. Then the circuit responds as follows: e_1 active triggers ET-1. e_2 or e_3 active alone gives no output. e_1 and e_2 active simultaneously triggers ET-1 and ET-2. Any other combination of two simultaneous inputs will only trigger ET-1 but not ET-2. All e's active simultaneously will trigger all the ET's

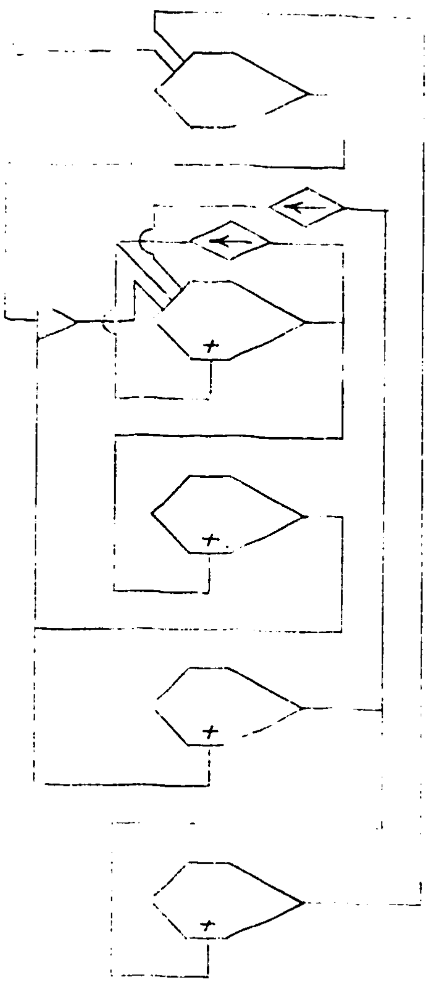
This circuit can be readapted to a different response by changing the order of the training environment application.

The above effects are short term effects with the present automaton.



Circuit 26

This circuit exhibits a gradually expanding wave of activity progressing from ET-1 through the ET's sequentially until ET-n becomes active. How far through this sequence the wave progresses is dependent upon the length of time e is active at the input. The individual ET's remain active after this initial transient which is very slow, until the input e ceases activity or becomes low in rep. rate. Then a similar wave progresses through the system, but in this instance the ET's become inactive sequentially along the connected system.



Circuit 27

This circuit exhibits autonomous action of more than just a simple type. For example, exciting it for a period of time with e will start a wave of activity through it similar to that in Circuit 26. If the e is then removed for a time, the activity will continue in a manner such that the waves start and stop in somewhat of a non-repetitive fashion, gradually ceasing after a long period of activity. During this period the circuit is fairly sensitive to various stimuli, some causing greater activity and some causing less activity. In fact, e, which originally excited the circuit to activity, will occasionally stop the activity completely. This is one of the types of activity which will be studied with the present automaton.

The above circuits are only indicative of some of the various systems which can be studied with the present automaton and are to be considered as only an extremely small sample of the total possible systems.

7. CONCLUSIONS

Experimental tests on components which have been developed to have functional behavior similar to biological neurons indicate that interesting adaptive behavior may indeed be possible with circuits composed of these components. For example, the initial test on the automaton which has been constructed from these components have shown that adaptive pattern recognizers, order detectors, and even circuits having certain autonomous pattern behavior are possible. These basic processes of adaptation are presently of only the most elementary type, but with greater environmental complexity, which involves more elaborate input transducers, it is felt that much greater adaptive functional behavior is possible.

Certain unpredicted effects with the automaton may be of more than passing interest. For example, when the automaton is operated with only portions of it actively connected into a system, those portions which are unconnected signal-wise but interdependent energy-wise, occasionally produce pulses in synchronism with each other and with the autonomous components. This is explainable in the automaton by incomplete filtering and by the individual Energy Transducer threshold settings. However, it has a correspondence in the biological system where the alpha rhythm is present in the inactive cortex.

In short, a form of "biological computer" is now available which is extremely flexible in its operation possibilities. Two methods of use of this automaton are open to the operator. The first method is that similar to the operation of an analogue computer in which the complete system connectivity is specified and the resulting details of operation are monitored when different prescribed environments are active. The second method is that similar to the interaction between a biologist and a living system in which various potential connectivities between the components are made rather randomly, and then the effects of various environments upon the functional connectivities are studied. This latter method is by far the most interesting and is the manner in which the automaton was meant to be used. Using this method, knowledge of various systems will be gained and catalogued so that more complex connective systems can be constructed.

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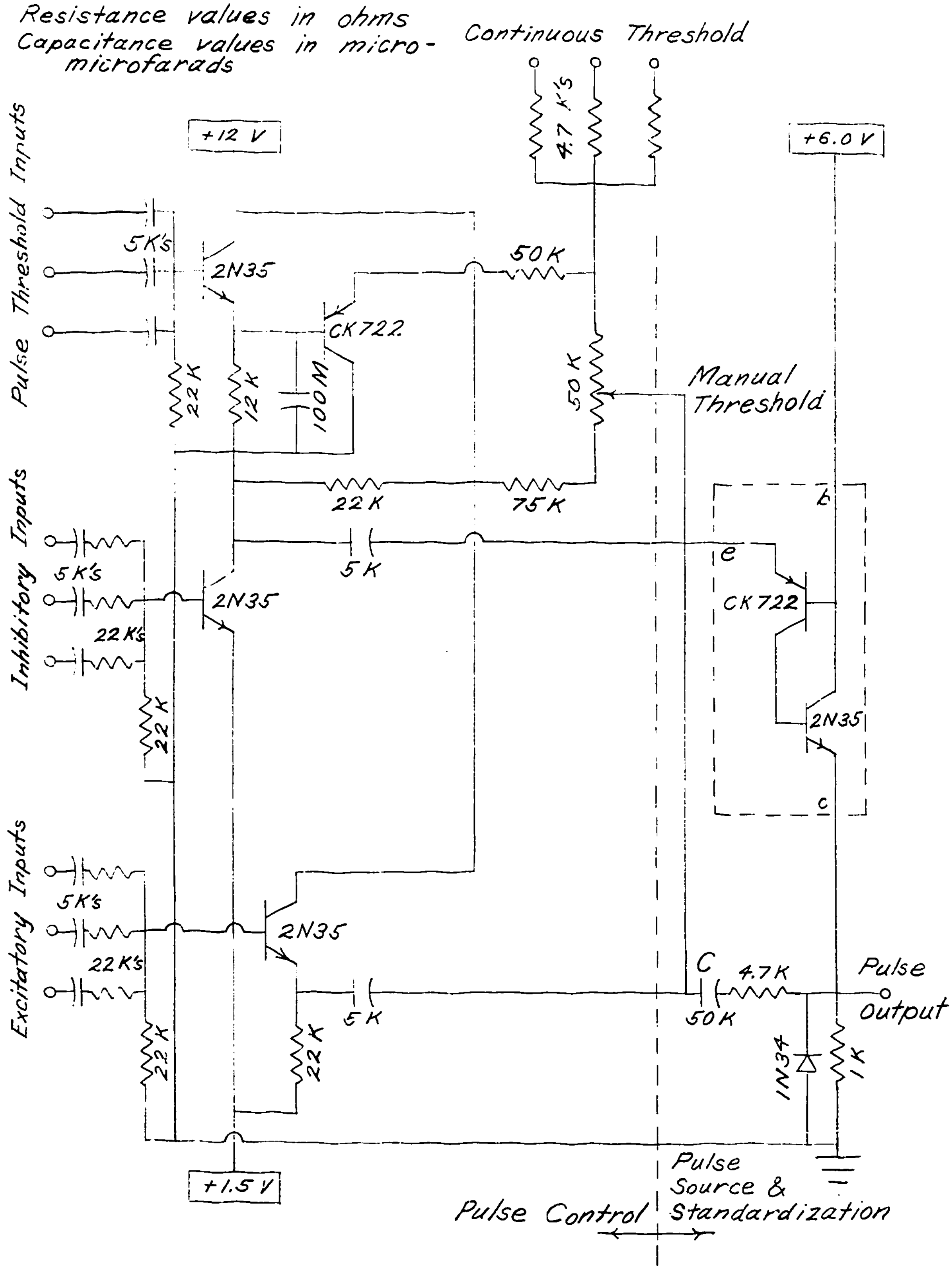
APPENDIX A

ENERGY TRANSDUCER

The Energy Transducer is composed basically of two functionally different circuit units. As shown in Figure 31, the section to the right of the vertical dashed line is the pulse source and standardization unit whereas the section to the left of the dashed line has the function of controlling the source and standardization unit. In connection with the latter section, Figure 32 differs from Figure 31 only in the pulse threshold input part of the control unit as will be explained later. At present, then, either figure may be considered.

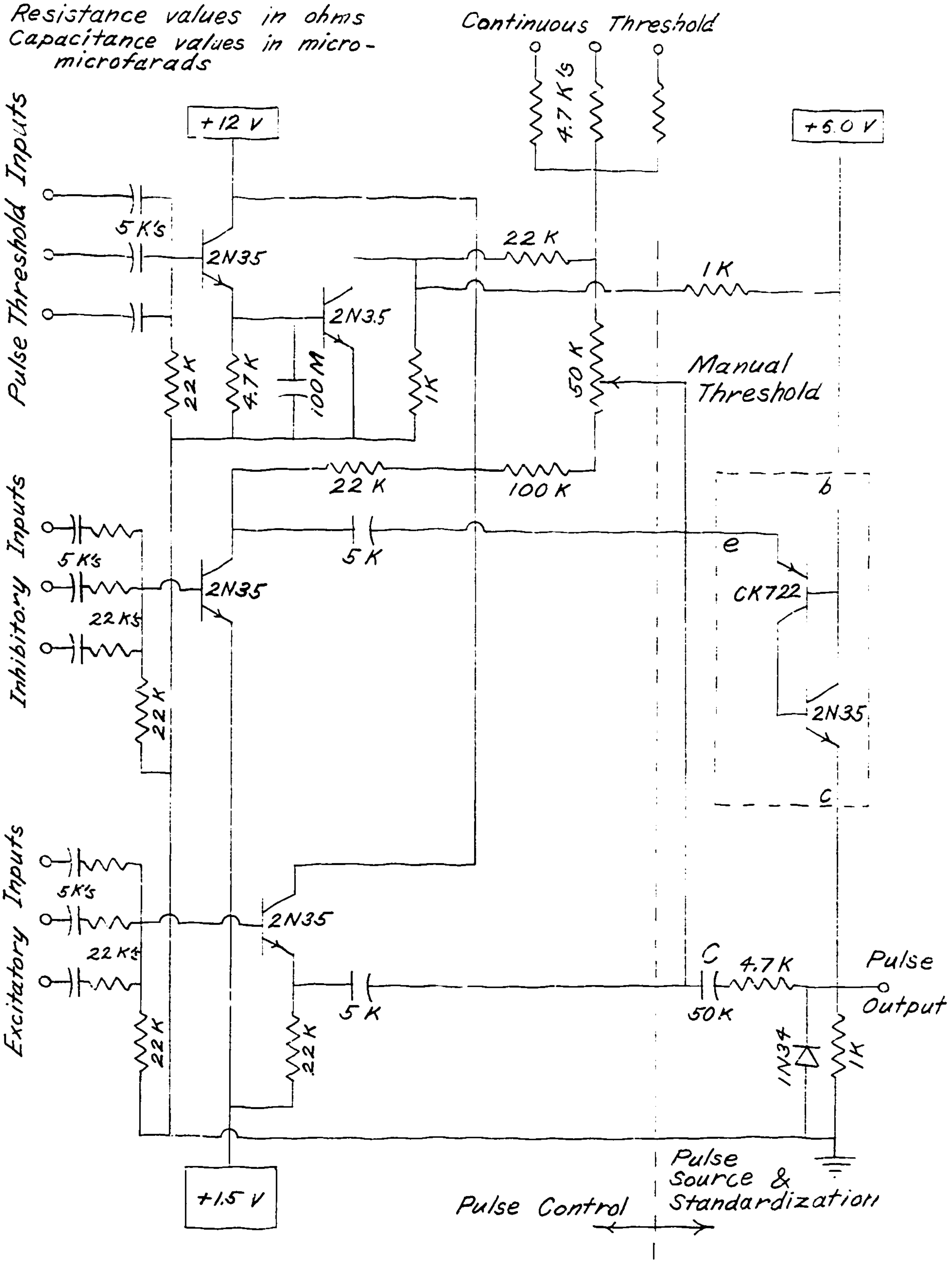
The pulse source and standardization unit is basically a monostable circuit which is triggered by pulses arriving from the pulse control unit. The active element of this monostable circuit is the composite transistor unit shown enclosed in dashed lines. This composite transistor consists of a CK722 and a 2N35 transistor connected together in a "hook-connected" transistor fashion. When connected in this manner and treated as a single transistor with the terminals e, b, and c corresponding to the emitter, base, and collector, the composite transistor unit has characteristics similar to a point contact transistor. In particular, it has an $\alpha > 1$ over certain ranges of operation and so will exhibit a region of negative resistance. It is this property which is useful in the present connection.

The quiescent condition of the composite transistor unit and the associated circuit is such that the c terminal is at ground potential, the b terminal is at + 6.0 volts potential, and the e terminal is at some potential less than + 6.0 volts. When the potential of the e terminal is raised above the potential of the b terminal, by means of a pulse of great enough magnitude arriving from



Resistance values in ohms
Capacitance values in micro-microfarads

Figure 31. (+) Energy Transducer (Decreasing Threshold)



Resistance values in ohms
Capacitance values in micro-
microfarads

Figure 32. (-) Energy Transducer (Increasing Threshold) the pulse control unit, the CK722 transistor conducts current. If the energy content of this current source is high enough to drive the CK722 into its saturated conduction region--and this will be true only above certain charge levels of the 5K micro-microfarad capacitor, C, connected between terminals e and c--then the composite transistor operating point is forced into the high current, low voltage region of its characteristic. This results in a rapid discharge of the above-mentioned capacitor, C. After discharge, the current source impedance increases to the point where the composite transistor cannot be held in its high conduction region and it returns to its former condition with the e terminal potential less than the b terminal potential. In this condition the capacitor, C, charges to its former quiescent condition over a period of time depending upon the charging current path resistance.

Simultaneously, with the discharge of the capacitor, C, and the high conduction condition of the composite transistor, it will be noticed that the potential difference between the terminals b and c is very small. Since the potential of the b terminal is fixed at + 6.0 volts, this means that the potential of the c terminal is raised to very nearly + 6.0 volts for the period of composite transistor high conductance, after which the potential of the c terminal returns to near ground. The result is a pulse of an amplitude of nearly 6 volts from a source whose output impedance is low--only a few tens of ohms.

Immediately following the pulse, the capacitor, C, is charged to its quiescent potential condition over a period of time depending upon the equivalent RC time constant of the circuit. This recovery time is about one to two milliseconds. At the very beginning of this recovery time, and for about one-fourth of the total time, the charge on the capacitor, C, is so low that it cannot support the composite transistor unit in the region of negative conductance. Therefore, during this time the pulse source unit cannot produce any pulses regardless if it is triggered or not. This is the period of absolute refractory time. Following this period is the period of relative refractory time during which the pulse source unit can only be excited by pulses of increased amplitude. After complete recovery, the pulse source can be triggered normally.

The pulse control unit of the energy transducer consists of three pulse input sections each with a different purpose; a constant level input called the continuous threshold input; and a manual threshold control. These different sections will now be explained.

The excitatory inputs consist of a summing network composed of the three 5K micro-microfarad capacitors and the 22K ohm resistors in the base circuit of a 2N35 transistor. The output of this network thus controls the 2N35 transistor amplifier output so that a positive pulse appears at the e terminal of the composite transistor previously described whenever a pulse, or pulse summation, of amplitude greater than 3.0 volts is present at the excitatory input. Depending upon the amplitude of the input pulses and upon the setting of the threshold level to be described later, the pulse source may be triggered and an output pulse may result. The summing network was arbitrarily chosen such that the summation is nonlinear; that is, the effect of two pulses of a given amplitude is not the same as that of a single pulse of twice the given amplitude. Also the time of summation of pulses was rather arbitrarily set at about 50 microseconds.

The inhibitory inputs are identical to the excitatory inputs except that a negative pulse appears at the e terminal of the composite transistor for pulses active at the input. The gain of the inhibitory amplifier is also such that identical simultaneous pulses at both the excitatory and inhibitory inputs will not cause an output pulse. That is, the inhibition imput has more gain than the excitatory input. The result is essentially a pulse-by-pulse inhibition.

The pulse threshold inputs are identical to the excitatory inputs through the first stage of amplification. After that, the circuits differ; in particular the pulses active at the pulse threshold inputs are integrated by the 100 M micro-microfarad capacitor. The result is a slowly varying voltage whose amplitude is a function of the input pulses. This voltage is then used to control a transistor, either a CK722 or a 2N35 as shown in Figure 31 and Figure 32 respectively. In Figure 31 this varying voltage causes the threshold potential of the e terminal to increase as the pulses active at the pulse threshold inputs increase in amplitude or in average repetition rate or both and the pulse source then becomes more sensitive to excitatory pulses--that is, the threshold of the energy transducer decreases. In Figure 32 the effect of the pulses at the pulse threshold inputs have the opposite effect as those in Figure 31. With respect to the time constant of integration of the pulse threshold inputs, it is many times that of the other pulse inputs, being a few seconds in value.

The continuous threshold input is merely a direct control of the threshold potential by any source of potential, either other energy transducers or external sources. Similarly, the manual threshold allows a direct control of the threshold by external means.

There is one element remaining to be explained in the energy transducer and that is the 1N35 diode across the output terminals. Its purpose is to clamp the output potential at ground with respect to any negative pulses appearing at the output because such pulses tend to trigger the pulse source unit if the threshold is at a low value and at present this may be undesireable.

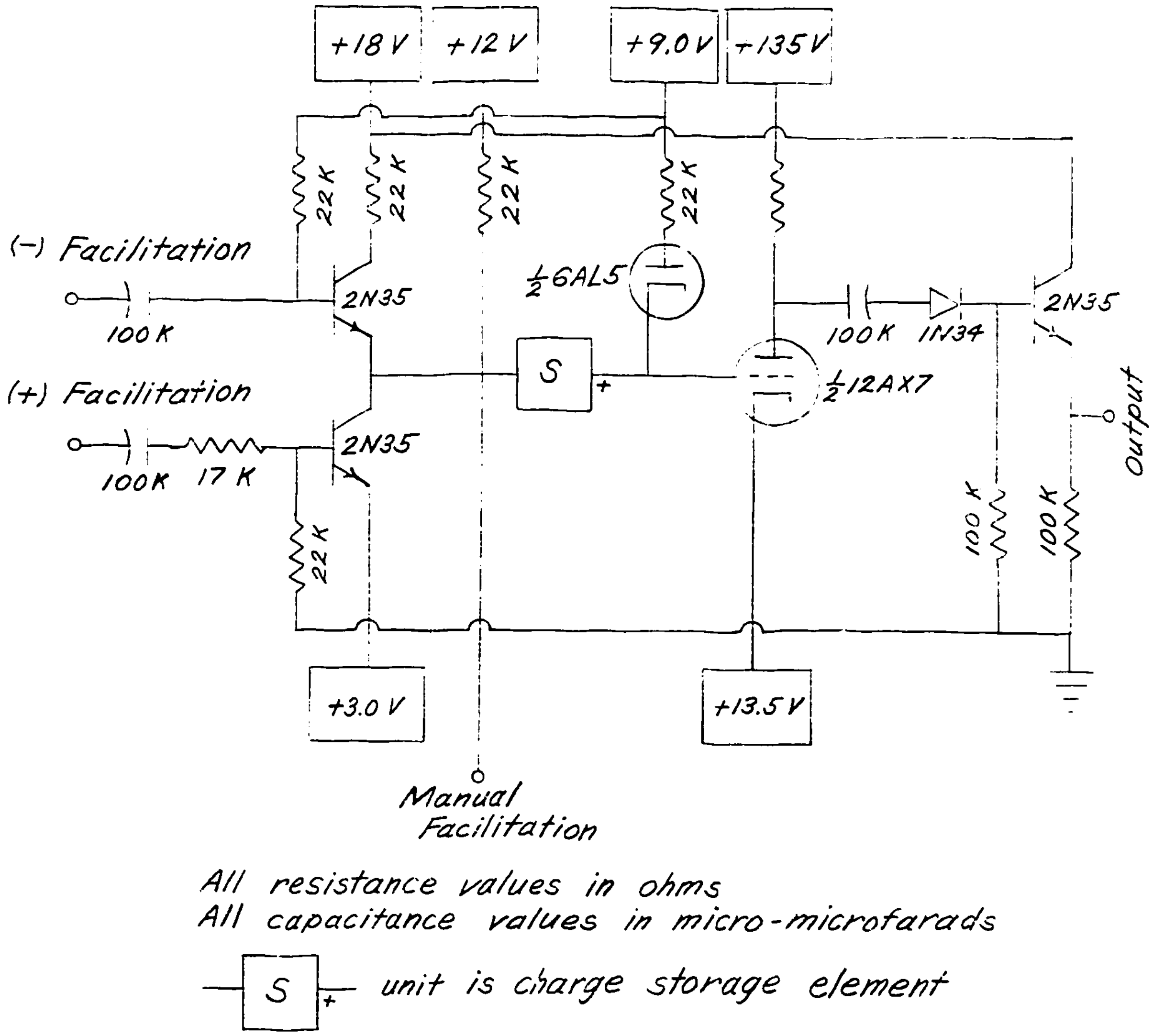
APPENDIX B

FACILITATOR

The Facilitator circuit shown in Figure 33 is wholly dependent upon the storage unit labeled S in the diagram and so an explanation of this unit seems to be in order. To provide a storage unit of any type, some physical state or states must be changed in a manner which is controllable and which is detectable. To be useful, the state must be established at the beginning of the storage time and, at some time later, this state must be measured with enough reliability to correlate the input datum with the output--that is, remembered--datum. There are many methods of storing data in use at present, but most of these systems are too eleborate and expensive to be considered as a sub-unit of any general elementary component--i.e. artificial neuron. Required for this purpose is a unit which is inexpensive, reasonably reliable for storage times of several minutes or perhaps tens of minutes, and whose associated input and output circuitry is reasonably simple.

As a result, several simple storage units were considered and experimented upon, among them being the position of a potentiometer tap, the electrolytic deposition of metals, the decompositon of an electrolyte into its constituent gases, simple charge storage on a capacitor, etc. Of these, the capacitor gave the most promising simple solution and so is the scheme presently being used.

However, for greater storage times and consequently more reliability, the S unit in Figure 33 may also be a completely discharged nickel-cadmium battery of extremely small size. This battery stores charge on its plates in a manner similar to an electrolytic capacitor but with an apparently much greater leakage resistance. Thus the time-constant of the battery is several times that of an



All resistance values in ohms
All capacitance values in micro-microfarads

unit is charge storage element

Figure 33. Facilitator

electrolytic capacitor with the result that long storage times are easily obtained.

For example, when the circuit of Figure 33 is used with a 200 microfarad, 3 volt electrolytic capacitor as the S unit, a storage time of 6 to 10 minutes can be obtained if the initial redistribution of charge on the plates and in the electrolyte are ignored. When the S unit is a 100 milliampere-hour nickel-cadmium battery, which is much smaller in physical size than the capacitor, a storage time of several hours can be obtained.

The Facilitator itself is basically a direct coupled two stage amplifier whose gain is dependent upon the total number of pulses which have been active at the (+) facilitation and the (-) facilitation inputs combined. The pulses which are active at the (+) facilitation input increase the facilitation and are reproduced at the output as pulses with increasing amplitude. The pulses which are active at the (-) facilitation input are effective only in decreasing the facilitation and are not reproduced at the output. Thus both positive and negative facilitation is available with only the positive facilitation data pulses being transferred to the output. In addition to pulse facilitation, manual facilitation is also possible. For example, grounding the manual facilitation terminal will give maximum facilitation and raising the manual facilitation terminal to + 13.5 volts will give minimum facilitation instantaneously. Any facilitation level may thus be obtained by the manual facilitation terminal.

The detailed operation of the Facilitator can be most easily understood if the transfer of a pulse from the input to the output is traced. Assume that the S unit has charge stored in it of such an amount that the voltage across it is one volt with the grid terminal positive. Also assume that a pulse of + 6 volt amplitude is impressed on the (+) facilitation input. The corresponding 2N35 transistor is driven into saturation conduction with the result that the potential of the negative terminal of the S unit is reduced to approximately + 6 volts. Thus the cathode of the 6AL5 diode is reduced in potential to about + 7 volts and the diode is driven into conduction. The result is a depletion of electrons from the grid terminal of the S unit and an increase in the voltage across the S unit. When the S unit has zero voltage across it, the circuit potentials are such that the bias of the 12AX7 triode is near cutoff. As the voltage across the S unit increases, the 12AX7 triode grid potential is raised above cutoff and the triode conducts current between pulses. Therefore when the S unit voltage is one volt, the triode is biased above cutoff and is conducting current between pulses. When the grid terminal is reduced in potential by the (+) facilitation input pulse, the grid of the triode is driven far below cutoff and a positive pulse appears at the output, the magnitude of which is dependent upon the voltage across the S unit.

Negative facilitation occurs when a + 6 volt pulse is impressed on the (-) facilitation input. This results in the corresponding 2N35 transistor conducting in saturation with a resulting increase in potential of the negative terminal of the S unit to about + 15 volts. The grid of the 12AX7 triode is thus driven above zero bias and grid current results. Therefore electrons are deposited on the grid terminal of the S unit and the S unit voltage is decreased. Ordinarily, driving the grid more positive would result in a negative output pulse. To prevent this the 2N35 transistor emitter follower in the output stage is biased at ground potential.

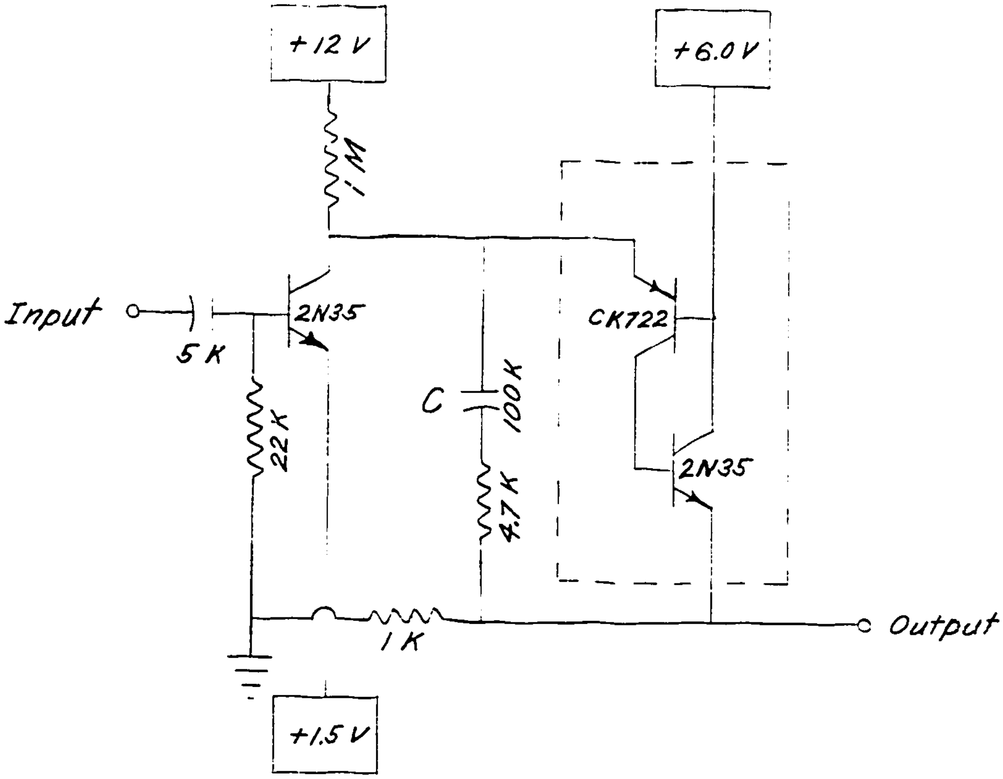
The facilitation circuit has several unique features. For example, for isolation of one end of the S unit electrically, vacuum tubes were required. This in turn makes it possible for the S unit to be interrogated by pulses of amplitudes up to + 3 volts without changing the S unit voltage. Also the gain of the (-) facilitation is such that it is about 5 to 10 times more effective in reducing the facilitation level for a given input pulse than is the (+) facilitation in increasing the facilitation level for the same pulse except when these pulses are simultaneously active at both inputs. Then the (-) facilitation gain is only slightly greater than the (+) facilitation gain. This allows the output of an Energy Transducer to control the level of facilitation of any Facilitator directly connected to its input.

APPENDIX C

AUTONOMOUS COMPONENT

The Autonomous Component shown in Figure 34 is simply a relaxation oscillator whose repetition rate can be controlled by selectively discharging the capacitive element. That is, the oscillator is a 1 M ohm resistor in series with a 100 K micro-microfarad capacitor. The active element is a composite transistor identical to that used in the Energy Transducer described in Appendix A. This produces a pulse in precisely the same manner as the pulse source in the Energy Transducer. However, in the Autonomous Component, capacitor, C, receives energy from a + 12 volt source and thus the potential of the emitter of the CK722 transistor can become greater than the + 6 volt potential at its base. Therefore the circuit is normally autonomous, producing a pulse output of repetition rate of about 10 pulses per second.

To prevent the Autonomous Component from producing an output when the input pulse repetition rate is above about 10 pulses per second, a 2N35 transistor is connected directly across capacitor, C. The input pulses are active on the base of this transistor, each pulse whose amplitude is greater than + 1.5 volts causing an emitter current in the transistor. Each time the transistor is thus activated, the collector potential decreases and the capacitor, C, is drained of some of its energy. If this process occurs often enough--as it does when the input pulses are + 6 volts in amplitude and have a repetition rate greater than 10 pps--then the potential of the CK722 emitter is kept below + 6 volts and no output pulse occurs.



All resistance values in ohms
All capacitance values in micro-microfarads

Figure 34. Autonomous Component